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**Design, implementation and characterization of a
kinematically aligned, cascaded spot-array generator
for a modulator-based free-space optical interconnect**

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This thesis is submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements of the degree of Master of Engineering

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Abstract

A large interest has been devoted to the use of optical interconnections in digital computer and digital telecommunication systems over the last few years. This interest is motivated by the promise of a greatly increased connectivity, lower power dissipation, and the compactness of interconnections that can be achieved with the use of this technology.

This thesis examines the design and the implementation of a modular spot-array generator for a modulator-based free-space optical interconnect. Two cascaded diffractive optical elements produce 4×8 clusters on a $1600 \mu\text{m} \times 800 \mu\text{m}$ pitch, where each cluster is a 4×4 array of $(1/e^2)$ $13.1\text{-}\mu\text{m}$ -radius spots on a $90\text{-}\mu\text{m}$ pitch. The spot-array generator is kinematically aligned to the interconnect system in such a way that it can be removed and reinserted without realignment. Characterization results are presented.

Sommaire

Au cours des dernières années, un grand intérêt a été consacré à l'utilisation d'interconnexions optiques dans des systèmes de télécommunication numérique et des ordinateurs numériques à haute vitesse. Cet intérêt est principalement relié à l'augmentation de la connectivité, la diminution de la puissance dissipée, et la compacité des interconnexions qui peuvent être réalisées en utilisant cette technologie.

La présente thèse examine la conception et la fabrication d'un module d'alimentation optique générant une matrice de faisceaux nécessaire au fonctionnement d'un démonstrateur de bus photonique fonctionnant à l'air libre. Deux éléments optiques diffractifs sont utilisés pour produire une matrice de 4×8 agglomérats sur un pas de $1600 \mu\text{m} \times 800 \mu\text{m}$, où chaque agglomérat est une matrice de 4×4 points lumineux ayant un rayon ($1/e^2$) de $13.1 \mu\text{m}$ sur un pas de $90 \mu\text{m}$. Le générateur de la matrice de faisceaux lumineux est aligné de façon kinématique au système d'interconnexion de façon à ce qu'il puisse être enlevé et réinséré sans avoir à être réaligné. Les résultats de la caractérisation du module sont également présentés.

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- Eric Bernier for the design of the interconnect baseplate and the characterization of the OPS module insertion into the interconnect baseplate (with the help of Michael Ayliffe);
- David Rolston for the design of the optoelectronic VLSI chip.

Although I was responsible for the design and the implementation of the OPS module, I would like to thank all of the above individuals for their help and suggestions in my endeavour.

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Chapter 1 - Introduction

1.1 - Motivation

The effects of recent technological improvements on our society are numerous, especially in the areas of computing and telecommunications. The shift towards the information driven society in which we live today started at the beginning of the 1980's with the introduction of fully digital transmission and switching networks. These networks introduced the ability to carry services in digital form from sender to receiver [1].

At the same time, optical fiber emerged as a viable transmission medium that provided long-haul transmission bandwidth at reduced cost. For this reason, optical fiber quickly became the predominant transmission medium for applications as diverse as intercity and transoceanic communication, as well as metropolitan and local area networks [1]. Furthermore, as optical fiber became omnipresent, the cost of long-distance digital services fell and this in turn led to rapid growth in demand. As data rates emerging from optical fibers continued to escalate, the nature of the traffic they carry was diversified. While telephone dominated the world of communications in the past, the availability of cheap transmission bandwidth encouraged planners to envisage a much greater mix of services. In particular, these include enhanced digital telecommunication services (high definition television, video conferencing, cellular, entertainment, the Internet, etc.) and advanced computer services (graphics, real-time image processing, pattern recognition, modeling, speech processing, etc.). The hardware platforms supporting these applications are based on digital integrated circuits (IC's) and their supporting interconnection technologies. As applications grow and mature they demand larger, faster, and more intelligent hardware platforms.

There has been significant progress in the fabrication of IC's because of an increased resolution of lithographic processes used in chip production. This has resulted in a scaling down of the minimum feature size achievable with more transistors being integrated on a single chip and gate delays being decreased. In turn, these factors have

had two major effects: increased clock speed and increased pin-out requirement [2]. This scaling down is expected to continue over the next few years as shown by the Semiconductor Industry Association (SIA) roadmap [3], which is presented in Table 1.1.

Table 1.1 – SIA projections for silicon ICs

Year	Feature size (μm)	Gate number (millions)	On-chip clock (MHz)	Off-chip clock (MHz)	Pin-out number (Rent's rule)
1995	0.35	0.8	200	100	980
1998	0.25	2	350	175	1640
2001	0.18	5	500	250	2735
2004	0.12	10	700	350	4026
2007	0.10	20	1000	500	5928

The reduction of interconnection delays, however, has been limited by the physical characteristic of metal lines that are used to establish connections. These physical limitations of electrical interconnections cause the following problems [4-8]:

- Metal interconnections are limited by the skin effect, which results in a greater attenuation in transmission lines at high frequencies. Furthermore, conventional conducting materials are lossy, resulting in high losses in electrical lines.
- Signal distortion in electrical interconnections increases with frequency and becomes a substantial problem at high modulation frequencies.
- Capacitive and inductive crosstalk coupled from signals on neighboring traces are another source of signal distortion, especially at high frequencies where electrical wires become very good antennas. Electromagnetic interference caused by unwanted outside signals being picked up is also a problem.
- Improperly terminated lines in electrical interconnections are a source of reflection, which causes signal distortion. This is often the case when multiple connections to a given signal line are made in parallel, which reduces the effective impedance.

- Signal distortion also results because of dispersion, i.e. when the interconnection delay varies with frequency.
- Synchronization problems occur because of clock and signal skew. This is due to the varying lengths and different paths of lines between set of logic gates, resulting in different transmission delays. This problem is exacerbated at higher speeds and longer distances.

All these undesired effects reduce the usable bandwidth of interconnections, typically to the hundreds of Mbits/s. Furthermore, the power dissipation required per pin-out for electrical interconnects limits the number of connections that can be realized on a chip or printed circuit board (PCB). In turn, this high power dissipation results in a thermal management problem.

Because gate delays have been decreasing while interconnect delays have remained constant, the speed at which circuits operate is dominated by interconnect delays rather than device delays [2]. That is, electronic designers are limited more by the communications capability between or within their chips than by the discrete gate performances. We can classify the interconnection problem into four categories: i) intra-chip, ii) chip-to-chip, iii) board-to-board, and iv) shelf-to-shelf communication. Although all four types of communications are limited by electrical interconnections, it is at the backplane level (board-to-board communication) that these limitations have more severe performance consequences [5-6].

A schematic diagram of an electrical backplane is shown in Figure 1.1. A backplane can be defined as a structure that provides mechanical and electrical support for high-speed communication between removable PCB's within a frame. The PCB's are connected to one another via an electrical bus, which usually comprises about 32 high-speed data lines. The total number of lines is limited by the size of the chassis, the minimum allowable line separation, and the dimension of the electrical connectors on the PCB. Given the increase of off-chip clock rates and the number of pinouts per chip, aggregate data rates will be in excess of a terabit per second within a few years [9]. Electrical backplane

technology will not be capable of supporting both the connectivity and bandwidth requirements of future systems, in part because of connector limitation [10]. Thus, it is at the backplane level of interconnection that optics provides the most significant advantage.

Figure 1.1 – Schematic diagram of an electrical backplane

1.2 - Advantages of Optical Interconnects

Optical interconnects may offer a way of circumventing some of the connectivity problems being encountered by digital processing systems. Before discussing the advantages of optical interconnections, it is useful to note that both electrical and optical signals are governed by electromagnetic physics: it is electromagnetic waves (and therefore photons) that carry signals [4]. However, the differences between electrical and optical interconnections are the higher frequency (500 THz compared to 10 MHz-10 GHz), shorter wavelength, and larger photon energy (2 eV compared to 40 neV-40 μ eV) of light compared to electrical signals [4]. These differences account for many of the potential advantages of optical interconnections over electrical ones. Another important

distinction to be made is the difference between the guided wave and the free-space approaches of optical interconnections. Guided-wave optical interconnections make use of a support medium to guide the wave from the transmitter to the detector. An example of guided-wave optical interconnection is the optical fiber. On the other hand, free-space optical interconnections (FSOI's) rely on lenses to direct the wave to its destination. FSOI's are favoured where short, two-dimensional high-density connections are required, such as backplanes.

A schematic diagram of an optical backplane is shown in Figure 1.2. Because electrical backplane standards typically demand a board-to-board separation of ~25 mm, optical backplanes must be compact enough to fit within this space. Given that this separation between boards is insufficient to allow the use of fiber bundles [6], optical backplanes are implemented using free-space optical links. The advantages of optical interconnections include the following [4-8]:

- The primary benefit of free-space optical interconnects is the additional dimension of connectivity that can be introduced. In an optical bus, signals are not confined to run along a single plane. By using the third dimension of space, an entire plane can be connected via optical imaging and the linear array of the electrical backplane can be extended to a two-dimensional array of optical data lines within the same physical space.
- Because the carrier frequency of light is very high compared with any frequency at which we can modulate, modulating the light beam makes essentially no difference to the propagation of light. Thus, there is no frequency-dependent loss, dispersion, or crosstalk when using light as the information carrier over relatively short distances.
- Because light beams propagate through one another in a linear medium without mutual interaction, there is very little crosstalk between neighboring signals. The small amount of crosstalk occurring is due to scattered light and spot coupling into an undesired window within the receiving device array.

- Impedances do not need to be matched between the emitter and the detector in optical interconnects because the current generated at the photodetector is dependent on the number of photons arriving and not on their electric field strength. Furthermore, impedance mismatch along the interconnection path as light travels through different materials can be eliminated by the use of simple quarter-wavelength resonators (anti-reflection coatings).

Other advantages include less signal distortion and dispersion, less sensitivity to electromagnetic interference, less clock and signal skew, and lower power dissipation per pin-out.

Figure 1.2 – Schematic diagram of an optical backplane

1.3 - Choice of Transmitter Technology for FSOI's

The two most widely investigated optoelectronic technologies for two-dimensional (2-D) free-space optical data transmission are arrays of multiple-quantum-well (MQW) modulators and of vertical-cavity surface-emitting lasers (VCSEL's) [11-13]. In emitter-based systems, the optical beams propagating in the interconnect are produced by arrays of VCSEL's that are directly modulated. This approach is attractive since the optical beams only have to be routed from the emitter to the detector, which significantly simplifies the optical system design. VCSEL's have many interesting optical characteristics [14,15] and significant progress in their development such as their integration to complementary metal-oxide semiconductor (CMOS) technology has recently been achieved [16]. However, the design of compact optical interconnects that possess a large number of optical channels would require large arrays ($>32 \times 32$) of single-mode VCSEL's demonstrating both good uniformity and stability that are hybridized to CMOS integrated circuits. At the time the research reported here was conducted such devices were not available. Furthermore, the current threshold uniformity and the thermal management of large VCSEL arrays remained a challenge.

Until VCSEL's exhibit the required characteristics for transmitters, modulator-based systems provide a good alternative [17-19]. They consist of electro-absorption modulators that are flip-chip bonded onto a VLSI integrated circuit and that are used to modulate an array of continuous wave (cw) constant power beams impinging on them. This is why modulator-based systems require the generation of 2-D arrays of beam off-chip. The array of sources must be aligned with the array of modulators, and the reflected beams become a signal to be sent to the detectors. Large arrays ($>32 \times 32$) of MQW modulators flip-chip bonded to CMOS with excellent characteristics have already been demonstrated [20]. This proven technology has been employed by many research groups for the realization of free-space optical interconnects.

1.4 - Thesis Outline

Recently, a modulator-based free-space optical interconnect was developed for optical backplane applications [21]. Modulator-based systems require that the modulators be illuminated with a 2-D array of uniform cw read-out beams. This requirement motivates the need to develop a suitable spot-array generator. In this paper, the design and the implementation of an array generator for such an optical interconnect is described.

Spot-array generators have been implemented using different techniques and packaging approaches [17-19,22]. However, to-date little emphasis has been placed on developing an array-generation system that is compact and modular and that can be aligned kinematically with the optical interconnect. It is advantageous for scalable multistage systems if optical array generators are designed as separate modules that are prealigned and then mounted on the system. Furthermore, it is important that such a module be easy to assemble. Finally, to facilitate test and repair, it is necessary that the module be designed such that it can be unmounted and remounted on the system without realignment. All these concerns have been addressed by the design of the spot-array generator for this system.

The format of this thesis is as follows: Section 2 presents a short overview of the optical interconnect system as well as the optical and optomechanical requirements for the spot-array generator. The optical power delivery system is described in Section 3. Section 4 presents the optical design of the cascaded array-generator system, whereas the optomechanical design is presented in Section 5. The assembly and the alignment procedures of the optical power supply (OPS) module are discussed in Section 6. Section 7 describes the kinematic alignment mechanism of the array generator to the optical interconnect. Finally, Section 8 presents characterization results.

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New sections not included in the paper have been added to this thesis and many sections have been expanded to provide either mathematical justifications or more details on the designs and the experiments.

1.5 - Original Contributions

The original contributions presented in this thesis are:

1. The design of a cascaded spot-array generator to act as an optical power supply in a modulator-based free-space optical interconnect. Although cascaded spot-array generators have been demonstrated, it is to the author's knowledge the first time that such an array generator is used as an optical power supply.
2. The design of a compact and kinematically aligned optical power supply that can be removed and reinserted without requiring any further adjustment.

1.6 - References

- [1] J. E. Midwinter, Photonics in Switching, Volume 1, Background and Components, Boston, Academic Press Inc., 1993, p.1-16.
- [2] J. W. Goodman, F. J. Leonberger, S.-Y. Kung, and R. A. Athale, "Optical interconnections for VLSI systems," *Proceedings of the IEEE*, Vol. 72, No. 7, p. 850-866, July 1984.
- [3] The National Technology Roadmap for Semiconductors, Semiconductor Industry Association, (1994).
- [4] D. A. B. Miller, "Physical reasons for optical interconnection," *International Journal of Optoelectronics*, Vol. 11, No. 3, p. 155-168, 1997.

- [5] R. A. Nordin, A. F. J. Levi, R. N. Nottenburg, J. O’Gorman, T. Tanbun-Ek, and R. A. Logan, “A systems perspective on digital interconnections technology,” *Journal of Lightwave Technology*, Vol. 10, No. 6, p. 811-827, June 1992.
- [6] F.A.P. Tooley, “Challenges in Optically Interconnecting Electronics,” *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 2, No. 1, p. 3-13, April 1996.
- [7] J. Jurgen and S. H. Lee, Optical Computing Hardware, Boston, Academic Press Inc., 1994, p.1-43.
- [8] J. E. Midwinter, Photonics in Switching, Volume 2, Systems, Boston, Academic Press Inc., 1993, p.169-250.
- [9] H. S. Hinton and T. H. Szymanski, “Intelligent Optical Backplanes,” Proceedings of the Conference on Massively Parallel Processing with Optical Interconnects, Oct. 23-24, Texas, 1995
- [10] R. Lord and S. Aujla, “High density backplane connector,” *Interconnection Technology*, Vol.10, No.1, p. 8-11, January 1994.
- [11] O. Kibar, D. A. Van Blerkom, C. Fan and S. C. Esener, “Power minimization and technology comparisons for digital free-space optoelectronic interconnections,” *Journal of Lightwave Technology*, Vol. 17, No. 4, p. 546-555, April 1999.
- [12] C. Fan, D. A. Van Blerkom, W. L. Hendrick, and S. C. Esener, “Free-space optical interconnection: a technology comparison of vertical-cavity surface-emitting lasers and multiple-quantum-well modulators,” *Optical Review (Japan)*, Vol. 3, No. 6A, p. 394-396, 1996.
- [13] A. L. Lentine, “Qualitative comparison of MQW modulator and VCSEL based OE-VLSI: a systems perspective,” *IEEE LEOS*, Vol. 2, p. 83-84, 1996.
- [14] L. A. Coldren, E. Hegblom, E. Strzelecka, J. Ko, Y. Akulova, and B. Thibeault, “Recent advances and important issues in vertical-cavity lasers,” *Proceedings of the SPIE*, Vol. 3003, p. 2-13, 1997.

- [15] R. A. Morgan, "Vertical-cavity surface-emitting lasers: present and future," *Proceedings of the SPIE*, Vol. 3003, p. 14-26, 1997.
- [16] A. V. Krishnamoorthy and K. W. Goosen, L. M. F. Chirovsky, R. G. Rozier, P. Chandramani, W. S. Hobson, S. P. Hui, J. Lopaata, J. A. Walker, and L. A. D'Asaro, "16 × 16 VCSEL array flip-chip bonded to CMOS VLSI circuit," *Topical Meeting on Optics in Computing*, April 13-16 1999, Snowmass, Utah, USA, Postdeadline Paper PD3-1.
- [17] D. V. Plant, A. Z. Shang, M. R. Otazo, D. R. Rolston, B. Robertson, and H. S. Hinton, "Design, modeling, and characterization of FET-SEED smart pixel transceiver arrays for optical backplanes," *IEEE Journal of Quantum Electronics*, Vol. 32, No. 8, p. 1391-1398, August 1996.
- [18] H. S. Hinton, T. J. Cloonan, F. B. McCormick, A. L. Lentine, and F. A. P. Tooley, "Free-space digital optical systems," *Proceedings of the IEEE*, Vol. 82, No. 11, p. 1632-1649, 1994.
- [19] D. T. Neilson, S. M. Prince, D. A. Baillie, and F. A. P. Tooley, "Optical design of a 1024-channel free-space sorting demonstrator," *Applied Optics*, Vol. 36, No. 35, p. 9243-9252, December 1997.
- [20] A. V. Krishnamoorthy and K. W. Goosen, "Progress in optoelectronic-VLSI smart pixel technology based on GaAs/AlGaAs MQW modulators," *International Journal of Optoelectronics*, Vol. 11, No. 3, p. 181-198, 1997.
- [21] B. Robertson, "Design of an Optical Interconnect for Photonic Backplane Applications," *Applied Optics*, Vol. 37, No. 14, p. 2974-2984, May 1998.
- [22] R. Iyer, Y. S. Liu, G. C. Boisset, D. J. Goodwill, M. H. Ayliffe, B. Robertson, W. M. Robertson, D. Kabal, F. Lacroix, and D. V. Plant, "Design, Implementation, and characterization of an optical power supply spot-array generator for a four-stage free-space optical backplane," *Applied Optics*, Vol. 36, No. 35, p. 9230-9242, December 1997.

Chapter 2 - System Overview and Spot-Array Generator Requirements

2.1 - Introduction

To establish the technical context of the work presented in this thesis, a short description of the Phase III optical backplane system demonstrator for which the spot-array generator was designed is provided in section 2.2. From this overview, specific optical and optomechanical requirements for the spot-array generator are established. This set of requirements is presented in Section 2.3.

2.2 - System Demonstrator Overview

The optical backplane system demonstrator developed at McGill University, which interconnects optoelectronic (OE)-VLSI chips in a unidirectional ring (see Figure 2.1), is designed to be scaleable (to an arbitrary even number of boards), modular (to allow easy assembly and maintenance), compact, robust, and misalignment tolerant.

Figure 2.1 – CAD drawing of the phase III optical backplane system demonstrator

2.2.1 - Optoelectronic Overview

A schematic diagram illustrating the operation of the optical backplane is shown in Figure 2.2. Each PCB is connected to an OE-VLSI chip. The OE-VLSI chips are based on GaAs/AlGaAs MQW electroabsorption modulators and p-i-(MQW)-n detectors which are flip-chip bonded to CMOS electronics and that operate at 852 nm for optical input and output. They have the digital circuit functions required to perform the necessary switching and routing functions, such as enabling optical data to be either transmitted, received, or re-transmitted at each OE-VLSI chip [1]. Electrical parallel data packets from a PCB are transferred to the OE-VLSI chip where they are converted into parallel optical data by modulation of a cw optical source and placed onto specific channels in the optical backplane. During the conversion, address headers are incorporated to the data packets such that the information can be routed to the correct PCB. When the optical data reaches its destination it is converted back into electrical data. A dual-rail data-encoding scheme is used such that two modulator devices are used to encode data differentially.

Figure 2.2 – Schematic diagram of the operation of an optical backplane

The architecture of the OE-VLSI chip was developed in conjunction with the optical interconnect in order to simplify both the chip architecture and the optical system. The optically interconnected chip is divided into an array of 8×8 clusters on a $800\text{-}\mu\text{m}$ pitch. Each cluster contains an array of 4×4 optical devices on a $90\text{-}\mu\text{m}$ pitch. The clusters are configured with alternate columns of modulator and receiver devices, which have sizes of $50\text{ }\mu\text{m}$ and $70\text{ }\mu\text{m}$ respectively. This geometry results in a device density of 2500 device/cm^2 . The optoelectronic chip layout geometry is shown in Figure 2.3. A summary of the optoelectronic chip characteristics is presented in Table 2.1.

Figure 2.3 – Optoelectronic chip layout geometry

Table 2.1 – Summary of the optoelectronic chip characteristics

Optoelectronic chip characteristic	Value
Operating wavelength of modulators & detectors	852 nm
Optoelectronic technology	GaAs/AlGaAs MQW
Number of optical channels	1024
Dual rail encoding	Yes
Number of data channels	256
Number of optoelectronic clusters	64 (8 × 8)
Optoelectronic cluster pitch	800 μm
Optoelectronic device array size	4 × 4
Optoelectronic device array pitch	90 μm
Device density	2500 devices/cm ²
Modulator size	50 μm
Detector size	70 μm
Beam waist at modulators and detectors	13.1 μm (1/e ² irradiance)
Hybrid attachment of optoelectronic chip	Flip chip bonded to CMOS
Optoelectronic die size	8 × 8 mm

2.2.2 - Optical Interconnect Overview

The optical interconnect design, which was published in reference 2, is a ring-based system that implements a point-to-point link between the modulators at one stage and the detectors of the subsequent stage. A schematic diagram of the optical interconnect system is shown in Figure 2.4.

The optical design is compact, alignment-tolerant, and includes several features. Optical data transmission is achieved by the modulation of an externally generated spot array, and the generation process of this array is divided in two stages. First, an array of 4 × 8 beams on a 1600 μm × 800 μm is first generated by the optical power supply (OPS) module. A second array generator (the fan-out grating on the PMG₁) then divides each of these beams into an array of 4 × 4 spots on the required 90- μm pitch. Another

characteristic of the interconnect is the microchannel-based relay system: arrays of 4×4 signal beams are transmitted simultaneously through each of the 8×8 array of symmetric $4f$ telecentric relays (see Figure 2.5) [3]. This provides a number of advantages over conventional or hybrid optics implementation, including compactness, low component count, minimal latency, low cost, and scalability [2].

Figure 2.4 – Schematic diagram of the optical interconnect

LA: lenslet array; Note that the array size of the OE-VLSI chip and lenslet array is 8×8 (and not 4×4 as shown), and that the PMG array size is 8×1 (and not 4×1 as shown)

The optically encoded data is routed from one stage to the next by means of polarization optics and patterned mirrors. Polarizing beam splitters are used either to reflect or transmit linearly polarized light, depending on its orientation relative to the plane of incidence. The state of polarization (SOP) is changed from linear to circular and vice versa by use of quarter-wave plates (QWP's) that have their slow axes oriented at 45° .

Figure 2.5 – Schematic diagram of a minichannel-based relay system

A description of the beam routing in the optical interconnect is now presented. The different states of light polarization in the interconnect system are shown in Figure 2.6. The array of 4×8 beams delivered by the OPS module is right-hand circularly polarized. When passing through the grating on the PMG_1 each beam is divided into a 4×4 array. The SOP is changed to p-linear as light passes through the QWP_1 such that the beams then propagate straight through the PBS_1 . The SOP again becomes right-hand circular after the QWP_2 and the light is focused on the modulators by the LA_2 . Upon reflection from the modulators, the beams are left-hand circularly polarized and they again pass through the QWP_2 where the SOP is changed to s-linear. The beams are then reflected off the PBS_1 and directed towards the second stage. After progressing through the relay module the light is reflected by the PBS_2 and passes through the QWP_3 , which changes the SOP to left-hand circular. When the beams are reflected off the patterned mirrors of the PMG_2 , the SOP is changed to right-hand circular and again to p-linear after passing through the QWP_3 . The beams thus propagate straight through the PBS_2 and the SOP is finally changed to right-hand circular after the QWP_4 . The beams are at last focused on the detectors by the LA_4 .

The optical interconnect is implemented using a modular approach (see Figure 2.4). This approach reduces the component count and the number of mechanical degrees of freedom to be aligned in the interconnect baseplate, which relaxes alignment tolerances [4].

Description and assembly techniques for the beam-combination, beam-relay and chip modules were already published [4-6].

Figure 2.6 – Light polarization states in the optical interconnect

2.3 - Optical Power Supply Requirements

2.3.1 - Optical Requirements

The system design requires that an array of uniform cw beams illuminates the modulators. Several design characteristics are required for the spot array. First, the design of the modulators, the detectors, and the diffractive optical elements were specified for an operating wavelength of 852.0 nm. Furthermore, the optical source of the system should provide linearly polarized light with an extinction ration that is greater than 100:1 so that the loss in the interconnect's power throughput is less than 1%. Second, the layout of the spot array must be the same as that of the modulators on the OE-VLSI chip, as shown in Figure 2.7. Third, for compatibility with the interconnect optics, the interconnect design requires that the $1/e^2$ spot radius at the modulators and the detectors be $13.1\text{ }\mu\text{m}$ [2]. Finally, the field curvature of the spot array should be minimized, whereas the power uniformity across the entire array should be maximized. Table 2.2 summarizes these requirements and presents the measured values for the implemented system (these characterization results are discussed in Chapter 8).

Figure 2.7 – Schematic diagram of the externally generated spot array

2.3.2 - Optomechanical Requirements

There are two main issues that must be addressed by the design of the optomechanics for the OPS module. First, the optomechanical support must ensure that all elements remain stable and well aligned to a common optical axis, while at the same time allowing them to be easily removed, replaced, and repositioned. Second, the optomechanical design must include a technique for mounting the OPS module onto the interconnect baseplate. The optical interconnect design requires that the optical axis of the OPS module be aligned at 90° to that of the interconnect system (as shown in Figure 2.4). To allow for simple replacement and repair procedures, it is also desirable for a kinematic-mounting mechanism to be developed such that the OPS module can be unmounted and remounted without requiring any realignment. Finally, the optomechanical design should be compact, robust, and easy to assemble, while minimizing cost.

An analysis of the tolerances for the alignment of the OPS module to the interconnect optics was presented in reference 5. The requirements listed in the second section of Table 2.2 represent the alignment tolerances associated with a 1% power loss in the optical power throughput through the interconnect. Because this metric is conservative, the system can still operate if these tolerance specifications are not met. However, a further increase in system misalignment will ultimately translate into lower operating speeds or larger bit error rates.

Table 2.2 – Optical requirements for the externally generated spot array

Optical requirements	Requirement	Measured
Wavelength	852.0 nm	852.0 ± 0.1 nm
4 × 8 array of cluster pitch	$1600 \mu\text{m} \times 800 \mu\text{m}$	$1602.2 \pm 0.4 \mu\text{m}$ $\times 801.5 \pm 0.2 \mu\text{m}^*$
4 × 4 cluster array pitch	$90 \mu\text{m} \times 90 \mu\text{m}$	$89.1 \pm 0.2 \mu\text{m}$ $\times 89.1 \pm 0.2 \mu\text{m}$
Beam waist at modulators ($1/e^2$)	$13.1 \mu\text{m}$	$\omega_x = 13.7 \pm 0.1 \mu\text{m}^*$ $\omega_y = 13.4 \pm 0.1 \mu\text{m}^*$
Input polarization linearity	100:1	1500:1
Optomechanical Requirements for a 1% loss in optical power throughput		
	Requirement	Measured
Roll around the optical axis	< 45 arc minutes (0.75°)	< 6 arc minutes (0.1°)
Lateral alignment repeatability	$55 \mu\text{m}$	$\sigma_x = 5.8 \mu\text{m}$ $\sigma_y = 4.1 \mu\text{m}$
Angular alignment repeatability	3 arc minutes (0.05°)	$\sigma_x = 0.004^\circ$ $\sigma_y = 0.006^\circ$

* Worst case out of four implementations

2.4 - Summary

An overview of the system demonstrator, the optoelectronic chip, and the optical interconnect was presented. The modulator-based system requires that the modulators be illuminated with a 2-D array of uniform cw readout beams. This requirement motivates the need to develop a suitable spot-array generator. An analysis of the system was performed in order to develop a set of well-defined requirements for the spot-array generator. In the following chapters, the optical and optomechanical design of the spot-array generator will be provided.

2.5 - References

- [1] D. R. Rolston, D. V. Plant, T. H. Szymanski, H. S. Hinton, W. S. Hsiao, M. H. Ayliffe, D. Kabal, M. B. Venditti, P. Desai, A. V. Krishnamoorthy, K. W. Goossen, J. A. Walker, B. Tseng, S. P. Hui, J. E. Cunningham, and W. Y. Jan, "A Hybrid-SEED Smart Pixel Array for a Four-Stage Intelligent Optical Backplane Demonstrator," *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 2, No. 1, p. 97-104, April 1996.
- [2] B. Robertson, "Design of an Optical Interconnect for Photonic Backplane Applications," *Applied Optics*, Vol. 37, No. 14, p. 2974-2984, May 1998.
- [3] D. R. Rolston, B. Robertson, H. S. Hinton, and D. V. Plant, "Analysis of a microchannel interconnect based on the clustering of smart-pixel-device windows," *Applied Optics*, Vol. 35, No. 8, p. 1220-1233, March 1996.
- [4] M. H. Ayliffe, D. Kabal, P. Khurana, F. Lacroix, A. G. Kirk, F. A. P. Tooley, and D. V. Plant, "Electrical, thermal and optomechanical packaging of large 2D optoelectronic device arrays for free-space optical interconnects," *J. Opt. A: Pure Applied Optics*, Vol. 1, No. 2, p. 267-271, March 1999.
- [5] F. Lacroix, B. Robertson, M. H. Ayliffe, E. Bernier, F. A. P. Tooley, M. Châteauneuf, D. V. Plant, and A. G. Kirk, "Design and Implementation of a Four-Stage Clustered Free-Space Optical Interconnect," *Proceedings of the SPIE*, Vol. 3490, p. 107-110, 1998.

- [6] B. Robertson, Y. Liu, G. C. Boisset, M. R. Taghizadeh, and D. V. Plant, "In situ interferometric alignment systems for the assembly of microchannel relay systems," *Applied Optics*, Vol. 36, No. 35, p. 9253-9260, December 1997.

Chapter 3 - Optical Power Delivery System Description

3.1 - Introduction

For the OPS module to provide the desired output, it is necessary that the light provided at its input be extremely well behaved. Before beginning to design the OPS module, it was necessary to establish how optical power would be delivered. Section 3.2 describes the light source specifications, that is the characteristics of the laser employed. Section 3.3 presents the design of the optical power delivery system. Finally, Section 3.4 presents the characteristics of the polarization maintaining (PM) fiber, which are required to develop the optical design of the optical power supply module.

3.2 - Light Source Specifications

The system described in section 2.2 requires each stage to be supplied with an array of constant optical power beams to illuminate the modulators. Two 500-mW lasers, model #SDL 8630 from Spectra Diode Labs, are used to deliver the required power to the system. This tunable laser utilizes an external grating for wavelength selection and stabilization. The characterized data from the laser manufacturer is shown in Table 3.1.

Table 3.1 - SDL 8630 characterized data provided by SDL

Laser Characteristic	Characterized data provided by SDL
Output power	500 mW at 1.92 Amps (at 21 °C)
Beam characteristics	Diffraction limited and collimated beam
Tuning range	845 to 865 nm
Center wavelength	855 nm
Spectral width	< 10 GHz
$M^2_{\perp}$	1.2
$M^2_{\parallel}$	1.5

The laser wavelength was adjusted to $\lambda = 852.0 \pm 0.1$ nm with the help of a fiber optic spectrometer (ist-rees model #E201). The output from the SDL 8630 is a collimated, slightly astigmatic and approximately Gaussian beam. Table 3.2 shows measured values for the beam diameter defined as $2\omega_0$ (where ω_0 is the radius that corresponds to a 13.5% clipping loss) along the length of the optical table. The axis is defined such that x refers to the direction parallel to the plane of the optical table surface and y to the direction perpendicular to the table. The distance is measured from the exit pinhole of the SDL laser.

Table 3.2 – Measured laser beam diameter at different distances from the laser output

Distance (± 1 cm)	x diameter (± 50 μm)	y diameter (± 50 μm)
50 cm	2850 μm	3600 μm
68 cm	2850 μm	3500 μm
83 cm	2850 μm	3250 μm

3.3 - Layout and Description of the Delivery System

Figure 3.1 presents a schematic layout of the power delivery system that supplies power to two OPS modules. Note that in order to supply optical power to all four OPS modules, two such delivery systems are required.

Figure 3.1 – Schematic layout of the power delivery system

Light is launched into the OPS module through a fiber-connect (FC) polarization-maintaining (PM) single-mode fiber. A fiber coupler (Oz Optics part # HPUC-23-850-p-6.2AS-11) is used to launch the light from the SDL laser into the PM fiber. The OZ couplers are placed approximately 50 cm from the exit pinhole in order to minimize the length of the optical train while still leaving enough space to place all the elements. The beam has a diameter of $3600\text{ }\mu\text{m}$ in y at that distance. In order to ensure optimum coupling efficiency, the OZ couplers need to receive collimated beams of about $1200\text{ }\mu\text{m}$ diameter. This was measured by operating a coupler in reverse mode, that is placing a fiber at the coupler output and measuring the output beam diameter. The beam emitted from the SDL needs to be compressed by a factor of ~ 3 to ensure a good coupling efficiency. This was achieved by placing 2 lenses with the proper focal length ratio in a telescope configuration at the SDL output. The chosen lenses, from CVI Laser Corporation, have focal lengths of 30 mm (#PLCX-17.2-15.5-C-852.0) and 100 mm (#PLCX-25.4-51.5-C-852.0), and are V-coated for 852.0 nm. This choice of lenses produces an astigmatic collimated beam of $1000 \pm 50\text{ }\mu\text{m}$ in x and $1320 \pm 50\text{ }\mu\text{m}$ in y (measured about 25 cm after the 30 mm lens).

An isolator is then placed to attenuate all reflections that could be fed back to the laser cavity and cause power and/or wavelength fluctuations. The throughput efficiency of the isolator was measured to be $88 \pm 1\%$. The OFR isolator possesses a Glan-laser polarizing prism at each end. Its output polarization is therefore linear and of excellent quality (extinction ratio $>100\,000:1$). A pellicle is placed at the output of the isolator in order to split the incoming light into two roughly equal power beams, each directed in separate OZ couplers. The pellicle was selected to effect the splitting because of its excellent polarization maintaining characteristics. It was experimentally verified that p-polarized incident light will be split with a $\sim 50/50$ ratio while preserving the quality of the incident polarization (this will not be true for other states of polarization incident on the pellicle). Attempts to split light with polarization incident at an angle relative to the pellicle will degrade the output polarization. A half-wave plate is thus used to adjust the incoming polarization such that it is incident on the pellicle at 0° . Note that the pellicle is mounted

on a kinematic mount that allows it to be removed and replaced while preserving a good coupling efficiency.

Finally, a half-wave plate is placed in front of each OZ coupler to adjust the incoming polarization with either the slow or fast axis of the PM fiber. Coupling efficiencies of 50% are easily realized while efficiencies around 65% are possible but more difficult to achieve. The light output from the PM fiber shows excellent polarization characteristics (extinction ratio of >1500:1). When the pellicle was removed, a throughput efficiency of 82.5% between the SDL output and the coupler input was measured.

3.4 - Polarization Maintaining Fiber Characteristics

The polarization-maintaining fiber used in the power delivery system is a PM jumper Fujikura PANDA fiber for 850 nm. The two extremities are FC connectorized, and the slow axis of the fiber is aligned with the polarization key of the connector. Table 3.3 provides the manufacturer characteristics of the fiber and the data measured by the distributor, JDS Fitel.

Table 3.3 – Panda fiber characteristics

Fiber Characteristic (at 850 nm)	Fujikura Specifications	JDS Fitel Measurements
Cladding diameter	$125 \pm 3 \mu\text{m}$	124.5 μm
Mode field diameter (MFD)	$5.5 \pm 1.0 \mu\text{m}$	5.6 μm
Core offset	-	0.7 μm
Cutoff wavelength	0.7 – 0.8 μm	0.7 μm
Attenuation (dB/km)	Max 3.0	2.0
Crosstalk	Max -25 dB/100 m	-34 dB/100 m
Length	-	100 m

The value of the fiber mode field diameter (MFD) is an important parameter in order to design the spot array generator, as it will be shown in section 4.3. However, when different experiments were performed with the fiber, the results were inconsistent with

the MFD value provided by JDS Fitel. Measurements were thus performed to calculate the fiber MFD. The Gaussian light propagation model utilized to measure the fiber MFD is now presented, followed by the MFD measurement and calculation.

3.4.1 - Theory for Evaluation of the Mode Field Diameter

The beam emitted from a cylindrical optical fiber has been mathematically and experimentally verified to approximate a Gaussian beam very closely [1 – Ch. 7]. For this reason, the Gaussian beam propagation model is used in all design calculations for the spot-array generator. The following equation derivation assumes that the reader has minimal knowledge of this model.

A beam exiting a fiber has its waist (ω_0) located at the output of the fiber. The mode field diameter of the fiber is equal to twice the beam waist. The following Gaussian beam propagation theory provides the dependence of the beam radius as a function of distance:

$$\omega(z) = \omega_0 \left[1 + \left(\frac{z}{z_0} \right)^2 \right]^{\frac{1}{2}} \quad \text{Equation 3.1}$$

where:

$$z_0 = \frac{\pi \omega_0^2}{\lambda} \quad \text{is the Rayleigh range} \quad \text{Equation 3.2}$$

$\omega(z)$ is the beam radius ($1/e^2$) at a distance z from the beam waist

ω_0 is the beam waist ($1/e^2$) (the fiber MFD is equal to $2\omega_0$)

Given that the fiber MFD is of the order of a few microns (i.e. $\sim 3 \mu\text{m}$), the Rayleigh range is of the same order of magnitude (i.e. $\sim 0.3 \mu\text{m}$). Because the distance z at which measurements are performed is much larger than the Rayleigh range, it is possible to approximate Equation 3.1 by:

$$\omega(z) = \omega_0 \left[\frac{z}{z_0} \right] \quad \text{Equation 3.3}$$

Substitution of Equation 3.2 in Equation 3.3 results in:

$$z = \frac{\omega(z)\omega_0\pi}{\lambda} \quad \text{Equation 3.4}$$

Furthermore, substituting $z+d$ for z in Equation 3.3 produces:

$$\omega(z+d) = \omega_0 \left[\frac{z+d}{z_0} \right] \quad \text{Equation 3.5}$$

The substitution of Equation 3.2 and Equation 3.4 in Equation 3.5 results in:

$$\omega(z+d) = \omega_0 \left[\frac{\omega(z)\omega_0\pi + d\lambda}{\pi\omega_0^2} \right] = \omega(z) + \frac{d\lambda}{\pi\omega_0} \quad \text{Equation 3.6}$$

When isolating ω_0 in Equation 3.6, we obtain an equation that allows the calculation of the Fiber MFD:

$$\omega_0 = \frac{d\lambda}{\pi[\omega(z+d) - \omega(z)]} \quad \text{Equation 3.7}$$

3.4.2 - Mode Field Diameter Measurement and Calculation

Performing measurements of the beam radius at different positions allows the calculation of the fiber MFD using Equation 3.7. Note that it is not necessary to know the distance between the fiber output and the location of the first measurement: only the relative distance between two measurements is required. A micrometer stage is used to precisely obtain the relative position of each measurement ($\pm 0.1 \mu\text{m}$) such that the fiber MFD can be calculated accurately.

Table 3.4 – Beam radius as function of distance (all data in μm)

$d (\pm 0.1)$	0	5000	10000	15000	20000	25000
$\omega (z+d)$ in x	822	912	999	1088	1179	1266
$\omega (z+d)$ in y	788	872	947	1032	1116	1198

$d (\pm 0.1)$	30000	35000	40000	45000	50000
$\omega (z+d)$ in x	1355	1445	1528	1609	1696
$\omega (z+d)$ in y	1288	1370	1453	1533	1620

Each set of two measurements in Table 3.4 provides a calculated value for the fiber MFD. The average value of ω_0 in both x and y was calculated, and the results are shown in Table 3.5. The calculated values differ from that measured by JDS Fitel, but they are within the manufacturer's specifications (i.e. $5.5 \pm 1.0 \mu\text{m}$). Note that the standard deviation of the MFD for different fibers was not calculated.

Table 3.5 – Calculated value of the fiber mode field diameter

MFD x	6.20 μm
MFD y	6.50 μm

3.5 - Summary

The light source's specifications and the optical power delivery system were presented. Furthermore, an experimental value for the fiber's MFD was calculated. It was important to obtain an accurate value for the fiber's MFD before defining the optical design of the spot-array generator, which is the subject of the next chapter.

3.6 - References

- [1] B. E. A. Saleh, M. C. Teich, Fundamentals of Photonics, Wiley & Sons Inc, New York (1991).

Chapter 4 - Optical Design of the Spot-Array Generator

4.1 - Introduction

The conception of the spot-array generator consisted of producing a design that met both the optical and optomechanical requirements. Although the optical specifications were developed first, they were influenced by the packaging strategy and by the optomechanics required to align the optical components. To facilitate presentation, the optical design is presented in this chapter whereas the packaging strategy and the optomechanics are presented in Chapter 5.

A review of the different array generation techniques is presented in Section 4.2. This is followed by a discussion of possible design choices in Section 4.3. Section 4.4 describes the optical design of the spot-array generator, which is a cascaded array-generation system. The design and optical components for the first stage (OPS module) and second stage of this system are presented in Section 4.5 and Section 4.6 respectively. To conclude, the design modeling performed with a ray tracing software and the simulations results are presented in Section 4.7.

4.2 - Review of Array Generation Techniques

Array generation is the process through which a single incoming beam of light is split into an array of spots in an output plane. This process is used in a variety of applications, such as multiple imaging, image processing, and optical data storage. Recently, there has been a large interest in array generation to supply optical power to arrays of optical switching devices.

The requirements for the array generators are determined by the characteristics of the devices. First, because all devices within an array are identical, the size and shape of the spot together with the direction of incidence of the beam onto the device must not vary

across the array. Second, the optical energy efficiency of the system must be large, while generating an array with uniform intensity. Numerous techniques exist to generate spot arrays meeting the above requirements. Streibl has proposed a classification in which the different techniques are grouped in three categories: (a) image-plane, (b) Fresnel-plane, and (c) Fourier plane array generators (as illustrated in Figure 4.1) [1].

Figure 4.1 – Spot array generation: (a) image plane using a lenslet array, (b) Fresnel plane using Talbot imaging, and (c) Fourier plane using a binary phase grating (from [5])

First, image-plane array generators use a special component located in an image plane conjugated to the array of devices. Optical systems utilizing lenslet arrays, Fresnel zone plates, holographic lenses, phase contrast imaging, and waveguides are all examples of such array generators. However, the spot array produced by these techniques inherits the profile of the incident beam, which often leads to inhomogeneity in the array.

Second, Fresnel-plane array generators include a Fresnel-diffraction step between a special component and the device array. An example of this type of array generator is based on the Talbot effect, where a phase grating is designed such that the diffracted light is concentrated in bright spots at a given distance from the grating. Although the inhomogeneity from the illuminating beam's intensity profile is averaged-out by the interference between multiple beams, there is still some inhomogeneity present in the output array.

Third, Fourier plane array generators rely on the Fourier transformation of a special diffractive component. This idea originated with Dammann and Gortler in 1971 [2] and was later explained in more detail in another paper by Dammann and Klotz [3]. Their goal was to obtain multiple images from one input object. There are two main reasons for which their approach for generating 1-D or 2-D arrays of spots is interesting [4]:

- i) The array generators are based on the use of phase gratings, which allow a high throughput of light energy.
- ii) The method uses binary gratings (referred to as Dammann gratings), which can be fabricated with planar fabrication techniques that have become standard in VLSI technology.

Furthermore, in contrast with the two previous methods, the homogeneity in Fourier plane array generators is dependent on the accuracy to which the periodic pattern is computed and fabricated (which can be controlled) and the overall profile across the array is independent from the incoming laser beam profile [5].

The Fourier plane array-generation technique has so far been the most widely used in free-space optical interconnects [5]. Although Dammann gratings are suitable in many situations, it can be necessary to improve the light efficiency of the array-generation system due to the limited power currently available from semiconductor lasers. When Dammann (or binary) gratings are used, losses are primarily due to light being diffracted into higher unwanted orders [6]. However, these losses can be reduced by using multilevel structures instead of binary phase gratings. Several papers discuss the design, fabrication, advantages, and error sources of multilevel gratings array generators [6-9].

4.3 - Design Choices

Various possibilities were examined for the design of the array generator. The most obvious solution would be to generate the entire spot array with a single diffractive optical element and a Fourier lens. However, to produce the required array of 512 beams and achieve good uniformity would require a diffractive optical element of at least 2048×2048 pixels [10], which would represent a significant design challenge. Another possibility would be to use an $8f$ optical system with two array generation stages consisting of a 8×4 generator and a single 4×4 array generator with three identical Fourier lenses (as demonstrated in reference 11). However, this scheme represents a bulky system that does not scale well. Furthermore, because the divergence required at the modulator array is determined by the design of the interconnection system and because the minilenses that are used to route light through the system are already in place in front of the modulators, it was desirable to also use those lenses as part of the array-generation system. The geometry of the clustered spot array (presented in Section 2.3) can easily be implemented by cascading two Fourier plane array generators. This consists of using the output of a first Fourier plane array generator as the input of a second one. A cascaded implementation possesses the advantage of producing a spot array with higher uniformity than that produced by a single Fourier plane array generator [11]. These decisions led to the design described in the next section.

4.4 - Cascaded Array Generation System Design

A schematic drawing of the array-generation system design is shown in Figure 4.2. Two Fourier plane array generators are cascaded to produce the required array of 512 beams. The first stage produces an array of 4×8 beams on a $1600 \mu\text{m} \times 800 \mu\text{m}$ pitch, which corresponds to the layout of the modulator clusters on the OE-VLSI chip. Each of these beams is then fanned out into an array of 4×4 spots on a $90\text{-}\mu\text{m}$ pitch. The Fourier plane array generators are computer-generated holograms implemented as a binary-level (4×8 fan-out) and multiple-level (4×4 fan-out) phase grating.

Figure 4.2 – Schematic diagram of the array generation process (in μm)

There are four lens transformations in the array-generation system:

- The collimation of the beam emitted from the fiber.
- The focusing of the collimated beam at the output of the Fourier lens.
- The collimation of the beam at the output of the OPS module.
- The focusing of the collimated beam onto the modulators.

It is possible to calculate the required beam waists in the array-generation system with the use of the Gaussian beam propagation model. Transmission of a Gaussian beam through a thin lens results in another Gaussian beam with a different radius of curvature and beam waist. Assuming that the incoming beam waist is located at the front focus of the lens, the resulting output beam waist of the transmitted beam is equal to:

$$\omega_0' = \frac{\omega_0}{\left[1 + (z_0 / f)^2\right]^{1/2}} \quad \text{Equation 4.1}$$

where f is the focal length of the lens and z_0 is the Rayleigh range (see Equation 3.2). If the depth of focus ($2z_0$) of the incident beam is much larger than the lens focal length f , Equation 3.8 can be approximated by:

$$\omega_0' \approx \omega_0 \left(\frac{f}{z_0} \right) \quad \text{Equation 4.2}$$

Substituting Equation 3.2 in Equation 4.2, we obtain:

$$\omega_0' \approx \frac{\lambda}{\pi \omega_0} f \quad \text{Equation 4.3}$$

A lens transformation of a Gaussian beam is shown in Figure 4.3, and the reader is referred to [12 – Ch.3] for details on the derivation of these formulas. Note that because the propagation of light is reversible, this equation is also applicable for a lens that is placed at the waist of an incoming beam. The calculated beam waists for all lens transformations are shown in Figure 4.2 and will be discussed in the following subsections. Note that because the optical interconnect system is telecentric, the beam waist at the focus of the Fourier lens ω_{FL} is the same as that at the modulators.

Figure 4.3 – Lens transformations of a Gaussian beam

4.5 - OPS Module Optical Design

The OPS module implements the first stage of the array-generation system. Because it is assembled and characterized separately, a separate set of requirements was developed for the OPS module. It is necessary for the module to produce an array of 4×8 collimated beams with a waist of $\omega_{OPS} = 176.0 \mu\text{m}$ on a $1600 \mu\text{m} \times 800 \mu\text{m}$ pitch. The optical design should provide a means of laterally translating the beams by $\pm 300 \mu\text{m}$ such that they can be aligned with the OE-VLSI chip after the OPS module is inserted into the interconnect baseplate. Finally, the state of polarization of the light must be right-hand circular for it to be routed properly in the interconnect system. The objective for the OPS

module optical design is to meet all these requirements while reducing the optomechanical complexity to a minimum. To do so, it is necessary that a number of optical and optomechanical degrees of freedom be incorporated in the design of the OPS module. These design items are presented in Table 4.1.

Table 4.1 – OPS module degrees of freedom to meet design requirements

Design Requirement	Optical / Optomechanical Solution
Spots on a uniform grid	Low distortion Fourier lens
Spot pitch of $1600\ \mu\text{m} \times 800\ \mu\text{m}$	Adjust the focal length of Fourier lens by changing the element separation
Spot size of $13.1\ \mu\text{m}$ ($1/e^2$)	Adjust the focal length of collimating lens by changing the element separation
Collimated beam through the FOG	Maintain the fiber facet at the front focus of the collimating lens
Angular alignment of the collimated beam	Adjust the fiber receptacle lateral position on the collimation barrel
Angular alignment of spot array about the optical axis	Rotate the FOG about the optical axis
Mutual angular alignment of chief rays of all beams in the spot array	Position the FOG at the front focus of the Fourier lens; Low aberration Fourier lens
Lateral alignment of the spot array	Rotate the Risley prism pair about the optical axis

A schematic diagram of the OPS module's optical design is shown in Figure 4.4. The light at the output of the fiber is collimated with the use of two lenses placed in a compound arrangement. This arrangement allows the effective focal length to be adjusted to the required value. Because the light at the output of the fiber is linear p-polarized, a quarter-wave plate is used to change the state of polarization to right-hand circular. A Risley prism pair is used to provide lateral alignment of the spot array. A Fourier plane array generator is then implemented by using a fan-out grating in combination with a Fourier lens. Finally, the beams are collimated by the lenslet array. The optical design of the OPS module together with a description of the different components is now be presented.

Figure 4.4 – Schematic diagram of the OPS module optical design

4.5.1 - Collimating Lenses

The Fourier plane array generator requires that a collimated beam with a given waist be incident on the fan-out grating. For design simplicity, it was decided to use off-the-shelf lenses placed in a compound arrangement to collimate the light from the fiber. The spacing between the lenses is variable to accommodate for variations in the divergence of the light emitted by the fiber and for variations of the lenses' focal length ($\pm 1\%$), such that the effective focal length of the compound arrangement can be precisely adjusted. Finally, note that for the output beam to be collimated, the fiber facet must be placed at the front focal length of the compound lens.

4.5.1.1 - Lens Combination Theory

The following discussion assumes that the reader is familiar with geometrical optics. Figure 4.5 illustrates a thick lens of effective focal length f_{eff} and of thickness t together with some points of interest: its focal points F_1 and F_2 , its principal points H_1 and H_2 , and its vertices V_1 and V_2 . The front focal length (ffl) and the back focal length (bfl) are the respective distances measured from the foci to its nearest vertex.

Figure 4.5 – Schematic diagram of a thick lens

It is possible to place two thick lenses in a compound arrangement in order to produce a lens system with a desired effective focal length. This is shown in Figure 4.6.

Figure 4.6 – Schematic diagram of two thick lens in a compound arrangement

The expression for the effective focal length is:

$$f_{eff} = \frac{f_1 f_2}{f_1 + f_2 - d} \quad \text{Equation 4.4}$$

where:

f_1 is the focal length of the first lens

f_2 is the focal length of the second lens

d is the distance between the lenses closest principal planes (i.e. H_{12} and H_{21})

Note that d is not the lens separation. In fact, the lens separation s is directly related to d after subtraction of the vertex to principal plane distances:

$$s = d - \overline{H_{12}V_{12}} - \overline{H_{21}V_{21}} \quad \text{Equation 4.5}$$

The distance from the front focal point of the lens combination to the first principal plane of the first lens is referred to as the front focal length of the compounded lens. It is obtained by:

$$m = \overline{F_1H_{11}} = \frac{f_1 (d - f_2)}{d - (f_1 + f_2)} \quad \text{Equation 4.6}$$

For more details on the derivation of these equations, the reader is referred to [13 – Ch.6].

4.5.1.2 - Design of the Collimating Lens

Because the beams reflected off the modulators will propagate through the interconnect, they will be slightly distorted due to the imperfect alignment of the components in the system. Thus, it is important for the beams at the modulators to have a waist of $\omega = 13.1 \mu\text{m}$. To evaluate the effective focal length required for the collimating lens, it is necessary to know both the fiber's MFD and the desired waist of the collimated beam. Using Equation 4.3, it is possible to derive the required waist radius of the collimated beam. Given that the required value for $\omega_{\text{FL}} = \omega_0$ is $13.1 \mu\text{m}$ and that the Fourier lens focal length is $f_{\text{FL}} = f = 30.00 \text{ mm}$, the required waist for the collimated beam is $\omega_{\text{CB}} = \omega_0 = 621.1 \mu\text{m}$. This value is then used in conjunction with the fiber waist in Equation 4.3 to find the required effective focal length for the collimating lens. However, because the fiber's MFD is different in x and y (see Section 3.4.2), a different effective focal length in both axes would be required to produce a collimated beam of $\omega_{\text{CB}} = 621.1 \mu\text{m}$ in both directions:

- i) Using $\frac{1}{2}\text{MFD}_x = \omega_0 = 3.10 \mu\text{m}$, the effective focal length should equal $f_{\text{eff}} = 7.11 \text{ mm}$.
- ii) Using $\frac{1}{2}\text{MFD}_y = \omega_0 = 3.25 \mu\text{m}$, the effective focal length should equal $f_{\text{eff}} = 7.44 \text{ mm}$.

Because these targets cannot be achieved using a symmetrical system (i.e. aspheric and achromatic lenses), we must determine the optimal value for the effective focal length for the collimating lens. The above calculations indicate that its value should be between 7.11 and 7.44 mm. The choice of the effective focal length must be based on the resulting spot size at the modulators (or equivalently, at the output of the Fourier lens). An analysis of the resulting spot size for different values of effective focal length is shown in Table 4.2. Because the modulator size is $50 \mu\text{m}$, it is preferable that the spot size be slightly smaller than the design value rather than larger. It was decided to design the collimating lens such that its effective focal length be $f_{\text{eff}} = 7.35 \text{ mm}$ (shaded row in Table 4.2).

Once the design value for the effective focal length of the collimating lens has been found, the lens selection is influenced by the following criteria:

- i) To reduce aberrations, it was decided to use either aspheric or achromatic lenses.
- ii) For design simplicity and to reduce cost, it was decided to use off-the-shelf lenses.
- iii) For practical reasons, the collimating lens thickness had to be kept below 25 mm.

Table 4.2 – Effect of the collimating lens effective focal length on the spot size

f_{eff} (mm)	ω_{fiber} (μm)	ω_{CB} (μm)	ω_{FL} (μm)
7.10	$x = 3.10$ $y = 3.25$	$x = 621.1$ $y = 592.5$	$x = 13.10$ $y = 13.73$
7.15	$x = 3.10$ $y = 3.25$	$x = 625.5$ $y = 596.6$	$x = 13.01$ $y = 13.64$
7.20	$x = 3.10$ $y = 3.25$	$x = 629.9$ $y = 600.8$	$x = 12.92$ $y = 13.54$
7.25	$x = 3.10$ $y = 3.25$	$x = 634.3$ $y = 605.0$	$x = 12.83$ $y = 13.45$
7.30	$x = 3.10$ $y = 3.25$	$x = 638.6$ $y = 609.2$	$x = 12.74$ $y = 13.36$
7.35	$x = 3.10$ $y = 3.25$	$x = 643.0$ $y = 613.3$	$x = 12.65$ $y = 13.27$
7.40	$x = 3.10$ $y = 3.25$	$x = 647.4$ $y = 617.5$	$x = 12.57$ $y = 13.18$
7.45	$x = 3.10$ $y = 3.25$	$x = 651.8$ $y = 621.7$	$x = 12.48$ $y = 13.09$

Table 4.3 and Table 4.4 illustrate the front focal length f_{fl} and the spacing d required for different combinations of commercially available lenses in order to produce the required effective focal length. For packaging considerations, the minimum spacing between the fiber and the first lens was set to 2 mm, whereas a minimum of 1 mm was considered sufficient for the distance d between the lenses. Furthermore, the sum of d and f_{fl} must be such that when added to the thickness of both lenses, the total is inferior to 25 mm (for compactness). The chosen combination is shaded in the tables: an $f = 6.26$ mm aspheric lens (Geltech #350110-B) and an $f = -20.14$ mm achromatic lens (Spindler & Hoyer #325220) are used. The lenses' specifications are given in Table 4.5 and CAD drawings for both lenses are shown in Figure 4.7.

**Table 4.3 – Value obtained for f/l given different commercial aspheric and achromatic lenses
(in mm, ‘-’ indicates a negative value)**

f_2	f_1												
	-25.00	-20.00	2.00	2.75	3.89	4.51	5.00	6.26	8.00	9.00	11.00	20.00	25.00
-25.00	-	-	2.59	3.56	5.03	5.84	6.47	8.10	10.35	11.65	14.23	25.88	32.35
-20.14	-	-	2.73	3.75	5.31	6.16	6.82	8.54	10.92	12.28	15.01	27.30	34.12
2.00	66.88	53.50	-	-	-	-	-	-	-	-	-	-	-
2.75	41.82	33.45	-	-	-	-	-	-	-	-	-	-	-
3.89	22.24	17.79	-	-	-	-	-	-	-	-	-	-	-
4.51	15.74	12.59	-	-	-	-	-	-	-	-	-	-	-
5.00	11.75	9.40	-	-	-	-	-	-	-	-	-	-	-
6.26	4.35	3.48	-	-	-	-	-	-	-	-	-	-	-
8.00	-	-	0.16	0.22	0.32	0.37	0.41	0.51	0.65	0.73	0.89	1.63	2.03
9.00	-	-	0.37	0.50	0.71	0.83	0.92	1.15	1.47	1.65	2.02	3.67	4.58
11.00	-	-	0.66	0.91	1.29	1.50	1.66	2.08	2.65	2.99	3.65	6.64	8.30
20.00	-	-	1.27	1.74	2.46	2.85	3.16	3.96	5.06	5.69	6.96	12.65	15.81
25.00	-	-	1.41	1.94	2.75	3.18	3.53	4.42	5.65	6.35	7.77	14.12	17.65

**Table 4.4 – Value obtained for d given different commercial aspheric and achromatic lenses
(in mm, ‘-’ indicates a negative value)**

f_2	f_1												
	-25.00	-20.00	2.00	2.75	3.89	4.51	5.00	6.26	8.00	9.00	11.00	20.00	25.00
-25.00	-	-	-	-	-	-	-	2.55	10.21	14.61	23.41	63.03	85.03
-20.14	-	-	-	-	-	-	-	3.27	9.78	13.52	21.00	54.66	73.36
2.00	-	-	3.46	4.00	4.83	5.28	5.64	6.56	7.82	8.55	10.01	16.56	20.20
2.75	-	-	4.00	4.47	5.18	5.57	5.88	6.67	7.76	8.38	9.63	15.27	18.40
3.89	-	-	4.83	5.18	5.72	6.01	6.24	6.84	7.66	8.13	9.07	13.30	15.66
4.51	-	-	5.28	5.57	6.01	6.25	6.44	6.93	7.60	7.99	8.76	12.24	14.17
5.00	-	-	5.64	5.88	6.24	6.44	6.60	7.00	7.56	7.88	8.52	11.39	12.99
6.26	2.55	3.29	6.56	6.67	6.84	6.93	7.00	7.19	7.45	7.59	7.89	9.23	9.97
8.00	10.21	9.77	7.82	7.76	7.66	7.60	7.56	7.45	7.29	7.20	7.03	6.23	5.79
9.00	14.61	13.49	8.55	8.38	8.13	7.99	7.88	7.59	7.20	6.98	6.53	4.51	3.39
11.00	23.41	20.93	10.01	9.63	9.07	8.76	8.52	7.89	7.03	6.53	5.54	1.07	-
20.00	63.03	54.42	16.56	15.27	13.30	12.24	11.39	9.23	6.23	4.51	1.07	-	-
25.00	85.03	73.03	20.20	18.40	15.66	14.17	12.99	9.97	5.79	3.39	-	-	-

Table 4.5 – Aspheric and achromatic lenses specifications

Lens property	Aspheric lens	Achromatic lens
Focal length at 852 nm (in air)	6.26 mm $\pm$ 1%	-20.14 mm $\pm$ 1%
Diameter	7.200 $\pm$ 0.015 mm	8.00 +0.00/-0.09 mm
Thickness	5.36 mm	2.8 $\pm$ 0.2 mm
Front focal length	2.899 mm	1.280 mm
Back focal length	0.859 mm	0.370 mm
Material	Corning C0550	SF10 / SSK51

Figure 4.7 – CAD drawing of the aspheric and achromatic lenses (in mm)

4.5.2 - Risley Prisms and Quarter-Wave Plate

A Risley prism pair is used to provide a $\pm 330\text{-}\mu\text{m}$ lateral adjustment of the spot array. The Risleys are 25 minutes steering wedges and have a diameter of 10.0 mm. The specifications are given in Table 4.6. Because the light at the output of the fiber is linear and p polarized, a QWP is used to change the state of polarization to right-hand circular.

Table 4.6 – Risley prism characteristics

Risley prism characteristic	Value
Wedge angle	25 minutes (0.417°)
Diameter	10.0 mm
Material	SF11 glass 785-258
Coating	V-coat for 850 nm

4.5.3 - Fan-Out Grating

The fan-out grating (FOG) is the first element of the Fourier plane array generator. The binary diffractive element has a period of $32\text{ }\mu\text{m} \times 64\text{ }\mu\text{m}$ and is designed to produce an array of 4×8 diffraction orders (odd-orders only). When used with an $f = 30.00\text{ mm}$

Fourier lens, the pitch of the 4×8 array is $1600 \mu\text{m} \times 800 \mu\text{m}$ and the beam waists are located at the back focal point of the Fourier lens. The FOG can be rotated to align the spot array with respect to the optical axis. A schematic diagram of the FOG is shown in Figure 4.8 and its characteristics are presented in Table 4.7.

Figure 4.8 – Schematic diagram of the fan-out grating (in mm)

Table 4.7 – Fan-out grating characteristics

Fan-out grating characteristic	Value
Generated array size	4×8
Generated array pitch (used with 30.00 mm Fourier lens)	$1600 \mu\text{m} \times 800 \mu\text{m}$
Aperture of the grating	$5000 \mu\text{m} \times 5000 \mu\text{m}$
Number of levels	2
Design wavelength	852 nm
Substrate dimensions	$14.0 \text{ mm} \times 14.0 \text{ mm}$
Substrate thickness	1 mm
Substrate material	Fused silica

4.5.4 - Fourier Lens

The Fourier lens is the second element of the Fourier plane array generator. The optical properties of the Fourier lens have an influence on numerous characteristics of the spot array at the output of the OPS module (see Table 4.1): The choice of the Fourier lens is thus an important one. A low distortion Fourier lens will produce a spot array on a uniform grid; a low aberration Fourier lens will increase the wavefront flatness; and the focal length of the Fourier lens will affect the pitch of the spot array. For these reasons, the first step in the optical design of the OPS module was the selection of a Fourier lens whose optical characteristics would produce the finest spot array.

A detailed description of the chosen Fourier lens, which was purchased from Heriot-Watt University, can be found in reference 14. The lens comprises five elements and achieves good correction for the achromatizing aberrations, such as spherical, astigmatism, and distortion. It also provides a large field size (7.7 mm) while maintaining low field curvature and distortion ($f\text{-sin}\theta$ distortion of less than 0.025% across the 20.7° field of view). The design allows the Fourier lens's focal length to be precisely adjusted to $f_{FL} = 30.00$ mm by variation of the spacing of the last element, which acts as a field flattener. This adjustment is necessary because the required focal-length control for achieving a $1\text{-}\mu\text{m}$ spot-position error is 1 part in 2000 [14]. Finally, the optical elements are packaged in a 416 magnetic stainless-steel barrel with an outer diameter of 25.00 mm. A schematic diagram of the Fourier lens is shown in Figure 4.9 and the lens' specifications are presented in Table 4.8.

Figure 4.9 – Schematic diagram of the Fourier Lens (in mm)

Table 4.8 – Fourier lens specifications (at 850nm)

Fourier lens characteristic	Value
Effective focal length (in air)	30.00 mm
F / #	4
Field	7.7 mm
Field of view	20.7 degree
Lens performance	0.051 waves rms
Front focal length	15.398 mm
Back focal length	5.626 mm
Coating	V-coating for 850 nm
Transmission efficiency	95.6%
Barrel dimensions	$\phi = 25.0$ mm $l = 53.1$ mm

4.5.5 - Lenslet Array

The last element of the OPS module is an array of 8×8 diffractive minilenses on a 800- μm pitch (the same as that of the optoelectronic window arrays on the OE-VLSI chip). The lenslet array has a focal length of $f_{LA} = 8.5$ mm and is used to collimate the beams at the output of the OPS module. A schematic diagram of the lenslet array is shown in Figure 4.10 and its specifications are given in Table 4.9. The features that are not described on the substrate are used for alignment purposes when the lenslet array is employed in other modules of the system [15]. Note that all minilenses used in this system have the same design and are eight-level diffractive elements.

4.6 - Second Stage Optical Design

The second stage of the array-generation system (as shown in Figure 4.2) consists of a fan-out grating in combination with a lenslet array that acts as a Fourier lens. The patterned-mirror grating (PMG) consists of four FOG stripes interlaced with four metal mirror stripes. The grating, which is an eight-level element, has a period of 161 μm and is designed to produce a 4×4 array on a 90- μm pitch when used in combination with an

Figure 4.10 – Schematic diagram of the lenslet array (in mm)

Table 4.9 – Lenslet array specifications

Table 4.10 Lenslet array characteristic	Value
Lenslet focal length (in air)	8.5 mm
Lenslet dimensions	800 × 800 μm
Array size	8 × 8
Array pitch	800 μm
Number of levels	8
Design wavelength	852 nm
Substrate dimensions	14.0 × 14.0 mm
Substrate thickness	1 mm
Substrate material	Fused silica

8.5-mm Fourier lens. The waist of the collimated beams produced by the OPS module must be incident upon the grating and the lenslet array must be placed at a distance f_{LA} from the PMG for each beam to be divided into the required spot array. A schematic diagram of the PMG is shown in Figure 4.11 and its characteristics are given in Table 4.10. The features that are not discussed are used to align the PMG in the beam-combination module [15], which is packaged in the interconnect baseplate. The metal

stripes are used in the interconnect to reflect data from the previous stage onto the receivers (see Figure 2.4). Finally, the lenslet array is packaged as part of the chip module [16].

Figure 4.11 – Schematic diagram of the patterned-mirror grating (in mm)

Table 4.10 – Patterned-mirror grating specifications

Patterned-mirror grating characteristic	Value
Generated array size	4 × 4
Generated array pitch (used with a 8.5-mm Fourier lens)	90 μm × 90 μm
Aperture of the grating stripes	800 μm × 6400 μm
Number of levels for the grating	8
Theoretical diffraction efficiency (including Fresnel losses)	87%
Design wavelength	852 nm
Metal mirror flatness	Better than $\lambda/10$
Metal stripes dimension	800 μm × 6400 μm
Substrate dimensions	14.0 mm × 14.0 mm
Substrate thickness	1 mm
Substrate material	Fused silica

4.7 - Design Modeling and Simulation

The optical design was modeled with the use of Oslo Six, a commercial ray-tracing software. The point-spread function and the Strehl ratio were calculated for the spots at the modulators. The calculations were performed for two different spots: the center spot, which is located on the optical axis (i.e., the zero order for both the FOG and the PMG), and the outer spot, which is the farthest from the optical axis in the 512-spot array. The outer spot is located at a distance of $3878 \mu\text{m}$ from the optical axis. Because the simulation software does not allow for array propagation, an equivalent optical system was designed by the modification of the period of the gratings such that a spot is produced on the y axis at the required distance from the optical axis.

The point-spread function, which is shown in Figure 4.12, indicates that the center and the outer spot radii ($1/e^2$) are $13.7 \mu\text{m}$, which is slightly larger than the Gaussian beam design value ($13.1 \mu\text{m}$). This minimal increase, which results in a spot of $3\omega = 41.1 \mu\text{m}$, can be tolerated by the oversized modulators ($50 \mu\text{m}$) and detectors ($70 \mu\text{m}$). The point-spread function also demonstrates that the system optical quality is good. The Strehl ratios for the center and the outer spots are, respectively, 0.892 and 0.886. These ratios indicate that aberrations are reduced to the Rayleigh limit [17], and the system can therefore be considered to be diffraction limited. Finally, Gaussian beam-propagation simulation confirmed the calculated beam waists presented in Figure 4.2.

Figure 4.12 – Simulation of the array generation system

4.8 - Summary

An overview of the different techniques for array generation was presented together with different design choices to produce the required spot array. A short review of the lens transformation of a Gaussian beam was presented as that theory is used to develop the optical design of the spot-array generator. It was decided that the optimal solution to produce the clustered spot array would be to use a cascaded spot-array generator. Thus, two diffraction stages are used to produce the final spot array. The first diffraction stage is designed as part of the OPS module, while the second stage is implemented as part of the optical interconnect design.

4.9 - References

- [1] N. Streibl, "Beam shaping with optical array generators," *Journal of Modern Optics*, Vol. 36, No. 12, p. 1559-1573, 1989.
- [2] H. Dammann and K. Gortler, "High-efficiency in-line multiple imaging by means of multiple phase holograms," *Optical Communications*, Vol. 3, No. 5, p. 312-315, 1971.
- [3] H. Dammann and E. Klotz, "Coherent-optical generation and inspection of two-dimensional periodic structures," *Opt. Acta*, Vol. 24, 505-515, 1977.
- [4] J. Jahns, M. M. Down, M. E. Prise, N. Streibl, S. J. Walker, "Dammann gratings for laser beam shaping," *Optical Engineering*, Vol. 28, No. 12, p. 1267-1275, 1989.
- [5] H. S. Hinton, An Introduction to Photonic Switching Fabrics, Plenum Press, New York, 1993, p. 282-293.
- [6] S. J. Walker and J. Jahns, "Array generation with multilevel phase gratings," *J. Opt. Soc. Am. A*, Vol. 7, No. 8, p. 1509-1513, August 1990.
- [7] J. N. Mait, "Design of binary-phase and multiphase Fourier gratings for array generation," *J. Opt. Soc. Am. A*, Vol. 7, No. 8, p. 1514-1528, August 1990.

- [8] J. M. Miller, M. R. Taghizadeh, J. Turunen, and N. Ross, "Multilevel-grating array generators: fabrication error analysis and experiments," *Applied Optics*, Vol. 32, No. 14, p. 2519-2525, May 1993.
- [9] R. L. Morrison, "Symmetries that simplify the design of spot array phase gratings," *J. Opt. Soc. Am. A*, Vol. 9, No. 3, p. 464-471, March 1992.
- [10] A. G. Kirk and T. J. Hall, "Design of computer generated holograms by simulated annealing: coding density and reconstruction error," *Optical Communication*, Vol. 94, No. 6, p. 491-496, 1992.
- [11] F. B. McCormick, "Generation of large spot arrays from a single laser beam by multiple imaging with binary phase gratings," *Optical Engineering*, Vol. 28, No. 4, p. 299-304, 1989
- [12] B. E. A. Saleh, M. C. Teich, Fundamentals of Photonics, Wiley & Sons Inc, New York (1991).
- [13] E. Hecht, Optics, 3rd Edition, Addison Wesley Longman Inc., New York (1998).
- [14] D. T. Neilson & al., "Optical design of a 1024-channel free-space sorting demonstrator," *Applied Optics*, Vol. 36, No. 35, p. 9243-9252, December 1997.
- [15] F. Lacroix, B. Robertson, M. H. Ayliffe, E. Bernier, F. A. P. Tooley, M. Châteauneuf, D. V. Plant, and A. G. Kirk, "Design and Implementation of a Four-Stage Clustered Free-Space Optical Interconnect," *Proceedings of the SPIE*, Vol. 3490, p. 107-110, 1998.
- [16] M. H. Ayliffe, D. Kabal, P. Khurana, F. Lacroix, A. G. Kirk, F. A. P. Tooley, and D. V. Plant, "Electrical, thermal and optomechanical packaging of large 2D optoelectronic device arrays for free-space optical interconnects," *J. Opt. A: Pure Appl. Opt.*, Vol. 1, No. 2, p. 267-271, March 1999.
- [17] Warren J. Smith, Modern Optical Engineering, Second Edition, McGraw-Hill Inc., Chapter 11, 1990.

Chapter 5 - Optomechanical Design of the OPS Module

5.1 - Introduction

For addressing the optomechanical requirements presented in Section 2.3.2, different packaging strategies are available. For example, a barrel assembly was employed in a previous implementation of an OPS [1]. However, it was found that the barrel assembly is not ideal for implementation. First, the components are not easily accessible when housed in a barrel: their insertion, removal and repositioning are tedious and time consuming. Second, the mounting of the barrel assembly onto a baseplate lacks sufficient insertion accuracy.

This chapter presents the optomechanical design of the OPS module. Section 5.2 describes the packaging strategy for the OPS module in order to address the optomechanical requirements. Sections 5.3 to 5.6 describe the different optomechanical components and their specifications.

5.2 - Packaging Strategy

The optomechanics for the OPS module must be designed to ensure that the fiber, collimating lenses, Fourier lens and lenslet array be accurately aligned to a common optical axis. Furthermore, the packaging must allow for the optical axis of the OPS module to be accurately aligned to the interconnect system when mounted onto the interconnect baseplate. The packaging strategy for the OPS module in this system consists of centering the optical components in 25.00-mm magnetic stainless-steel cells and then depositing them onto a baseplate. The baseplate is made of a rectangular slot with two precision-ground rods positioned in the corners of the slot, the rods acting as rails for the cells. Rare-earth magnets (Edmund Scientific part #H38428) are glued onto the bottom of the slot; they constrain the cells laterally and angularly. This strategy is similar to that presented in References 2 and 3 in which either a V groove or a

rectangular is used to support the components and define two reference axes for their alignment. Of these two strategies the V groove provides the most effective alignment because the line of contact on the baseplate lies on a planar surface (as opposed to a sharp corner in the case of the rectangular slot). Indeed, the drawback to rectangular-slot baseplates is their poor alignment repeatability owing to the degradation of the edge's sharpness after repeated insertions. On the other hand, the drawback to V grooves is an increase in machining costs. The baseplate approach that is proposed here combines both of these advantages: alignment repeatability and ease of machining. Furthermore, a derivative and significant advantage for using rods as an alignment reference is that they can be used to align the OPS module kinematically to the interconnect baseplate because they define the optomechanical axis of the OPS module. The mounting technique of the OPS baseplate to the interconnect baseplate is described in Chapter 7.

A schematic diagram of the optomechanics is shown in Figure 5.1, and the different optomechanical components are described in the following subsections. In the discussion, lateral alignment refers to the direction perpendicular to the optical axis of the OPS module (x - y), whereas longitudinal alignment refers to the direction of light propagation, that is parallel to the optical axis of the OPS module (z).

5.3 - Optical-Power-Supply Baseplate

The support for the cells of the OPS module consists of a slot baseplate 150 mm (long) $\times$ 40 mm (wide) $\times$ 15 mm (high) with the two extremities being 25 mm high. For ease of machining and reducing weight the OPS baseplates are machined out of aluminum. The baseplate is also compatible with $\phi 25$ -mm commercial optomechanical components so that the OPS modules can easily be assembled and characterized separately.

Figure 5.1 – Schematic diagram of the OPS module optomechanics

The specification for the precision ground rod diameter is $5.000 +0.000/-0.005$ mm, whereas the length of the rod is 175 mm (Nordex part #AAS-B9-523). For accurately defining the distance between the rods and ensuring their parallelism two alignment holders are used to position and align the rods on the OPS baseplate. Each holder consists of a rectangular piece through which two holes providing a tight sliding-fit clearance for the rods have been machined (see Figure 5.3). The holes on the holders are machined such that their position is within 5 μm of the design value. After the rods have been inserted into the alignment holders, the holders are attached to each end of the OPS baseplate. The rods are then glued in place using a strong epoxy, and the holders are removed. Because the rods are aligned with the help of holders, the machining tolerances of the OPS baseplate, such as the position and the width of the slot, can be relaxed. Only one pair of holders is necessary to align the rods on all four OPS baseplates.

Figure 5.2 – CAD drawing of the OPS baseplate (in mm)

Figure 5.3 – CAD drawing of the rod alignment holder (in mm)

5.4 - Cell Holders

All cells are machined out of 416 stainless steel such that they can be held in place by the magnets in the OPS baseplate during their alignment. The lateral alignment of the QWP, the RPP's, and the FOG is not critical. For this reason, the components are positioned manually and glued to 25-mm cells, for which the outer diameter tolerance has been relaxed. A CAD drawing of the Risley prism/QWP holder is shown in Figure 5.4. The holder for the FOG is similar, but the thickness of its cell edge is slightly smaller (2 mm).

Figure 5.4 – CAD drawing of the Risley holder (in mm)

On the other hand, the fiber, collimating lenses, Fourier lens, and lenslet array must be aligned accurately to a common optical axis. To do so requires that the components be centered within cells machined to an outer diameter of 25.00 ± 0.01 mm. The lenslet-array alignment technique utilizes lithographically defined metal markers that are deposited on the substrate during the lenslet-etching process. The lenslet array is centered relative to its cell by the alignment of the markers present on the substrate to those machined on the cell. It is then fixed by use of UV-cured epoxy; its alignment precision to the optomechanical axis of the cell was measured to be within $30 \mu\text{m}$. The CAD drawing of the lenslet array holder is shown in Figure 5.5.

5.5 - Collimation Barrel

It was decided to mount the fiber and the collimating lenses in a single barrel, referred to as the collimation barrel. This approach allows the collimating module to be easily inserted and removed from the OPS module, while maintaining alignment and collimation accuracy. Figure 5.6 presents a schematic diagram of the collimation barrel assembly, while a CAD drawing of the barrel is shown in Figure 5.7.

Figure 5.5 – CAD drawing of the lenslet array holder (in mm)

Figure 5.6 – Schematic diagram of the collimation barrel (in mm)

Figure 5.7 – CAD drawing of the collimation barrel (in mm)

The interior of the collimation barrel is divided into two sections by a stopper: The fiber receptacle is placed on one side, whereas the collimating lenses are inserted on the other side. The longitudinal positions of the lenses are adjusted by a combination of spacers inserted between both the stopper and the first collimating lens and between the two lenses. The spacers and the lenses are held in place with a retainer ring that is fixed by use of four screws. Finally, the design of the collimation barrel includes a groove to allow easy access to the cells inside the barrel.

5.5.1 - Packaging of the Collimating Lenses

The aspheric and achromatic lenses are first mounted in Delrin cells by use of an interference fit between the cell and the lens-edge surface. This type of fitting automatically centers the lenses to the mechanical axes of their cells. It has been shown in reference 4 that the optimal value for the cell's inner diameter (ϕID_{cell}) is between 2 μm and 20 μm smaller than the diameter of the lens (ϕOD_{lens}). Measured values for the diameters of the aspheric and achromatic lenses are shown in Table 5.1. Because machining one different cell for each lens would have been too expensive, the minimum number of different designs to meet the above requirement was derived from the table:

two different cell designs are required for the achromatic lenses, while only one is necessary for the aspheric lenses.

The outer diameters of the Delrin cells are machined to provide a close sliding-fit clearance to the inner diameter of the collimation barrel so that they can easily be inserted and removed from the barrel, while ensuring their alignment with its optomechanical axis. A CAD drawing of the design for the achromatic lens' cell is shown in Figure 5.8. The designs of the aspheric lenses' cells are identical except for different inner diameters (ϕID_{cell} , see Table 5.1) and a thickness of 6.2 mm.

The easiest way to insert the lenses is to first heat the cells to make them expand. The lenses are then inserted and the cells are cooled down to room temperature. As the cells cool and shrink, the lenses are snugly held in place. Because of the interference fit, the outer diameters of the cell increase (between 10-25 μm) once the lenses have been inserted. Thus, when the cells are first machined, their outer diameter is made slightly larger than the design value. Only when the lenses have been inserted are the outer diameters of the cells precisely machined to provide a sliding fit clearance when they are placed inside the collimation barrel.

Table 5.1 – Measurement of the lenses ϕOD , and cell ϕID specifications

Lens	Min ϕOD_{lens} (± 0.001 mm)	Max ϕOD_{lens} (± 0.001 mm)	ϕID_{cell} specification (± 0.005 mm)
Aspheric #1	7.216	7.219	7.204
Aspheric #2	7.213	7.216	7.204
Aspheric #3	7.213	7.216	7.204
Aspheric #4	7.211	7.213	7.204
Aspheric #5	7.203	7.205	7.193
Achromat #1	7.977	7.983	7.965
Achromat #2	7.977	7.980	7.965
Achromat #3	7.976	7.979	7.965
Achromat #4	7.974	7.978	7.965
Achromat #5	7.972	7.976	7.965

Figure 5.8 – CAD drawing of the achromatic lens cell holder (in mm)

5.5.2 - Fiber Centering Mechanism

The mechanism for centering the fiber with the optomechanical axis of the collimation barrel is shown in Figure 5.9. The end plate of a fiber-connect physical-contact (FC/PC) fiber receptacle is chamfered down at 45°, as shown. The fiber receptacle is placed in contact with the stopper of the collimation barrel and four cup-point-locking screws (to minimize backlash and provide stable positioning) are driven against the chamfered edge to hold the receptacle in place. The screws are then used to adjust the lateral position of the fiber receptacle. Using this mechanism allows the fiber to be centered to the optomechanical axis of the collimation barrel with a precision of better than 6 μm . Furthermore, after numerous removals from and insertions into the receptacle of the fiber, the deviation of the fiber from its initial position is within 1 μm . This mechanism is an improved version of that presented in Reference 1 in which the receptacle was chamfered down in a circular fashion and permitted an alignment precision of 10 μm .

Figure 5.9 – Schematic diagram of the fiber centering mechanism

5.6 - Summary

The packaging strategy for the OPS module was presented. A combination of a slot baseplate and precision ground rods is used to support the cells in which the optical elements have been mounted. This technique allows for the machining tolerances of the OPS baseplate to be relaxed, which is cost effective. Another significant advantage of this technique is the kinematic alignment of the OPS module to the interconnect baseplate that can be achieved using the rods on the baseplate. This will be further discussed in Chapter 7.

5.7 - References

- [1] R. Iyer, Y. S. Liu, G. C. Boisset, D. J. Goodwill, M. H. Ayliffe, B. Robertson, W. M. Robertson, D. Kabal, F. Lacroix, and D. V. Plant, "Design, Implementation, and characterization of an optical power supply spot-array generator for a four-stage free-space optical backplane," *Applied Optics*, Vol. 36, No. 35, p. 9230-9242, December 1997.

- [2] J. L. Brubaker, F. B. McCormick, F. A. P. Tooley, J. M. Sasian, T. J. Cloonan, A. L. Lentine, S. J. Hinterlong, and M. J. Herron, "Optomechanics of a free-space photonic switch: the components," *Proceedings of the SPIE*, Vol. 1533, p. 88-96, July 1991.
- [3] F. B. McCormick, F. A. P. Tooley, J. L. Brubaker, J. M. Sasian, T. J. Cloonan, A. L. Lentine, R. L. Morisson, R. J. Crisci, S. L. Walker, S. J. Hinterlong, and M. J. Herron, "Optomechanics of a free-space photonic switch: the system," *Proceedings of the SPIE*, Vol. 1533, p. 97-114, July 1991.
- [4] G. C. Boisset, M. H. Aycliffe, B. Robertson, R. Iyer, Y. S. Liu, D. V. Plant, D. J. Goodwill, D. Kabal, and D. Pavlasek, "Optomechanics of a four-stage hybrid-self-electro-optic-device-based free-space optical backplane," *Applied Optics*, Vol. 36, No. 29, p. 7341-7358, October 1997.

Chapter 6 - Assembly and Alignment

6.1 - Introduction

In order to produce the desired spot array, it is important that the optical components of the OPS module be properly aligned. While developing the optical and optomechanical designs of the OPS module, an assembly procedure was simultaneously drafted to ensure that all critical alignment tolerances could be achieved. This chapter presents the assembly and alignment procedure together with a characterization of the alignment techniques that were developed to package the OPS module. Section 6.2 presents the diagnostic substrate developed to characterize the alignment accuracy of numerous component in the system. The assembly of the collimation barrel is described in Section 6.3, whereas Section 6.4 discusses the adjustment of the Fourier lens focal length. Finally, the assembly and alignment of all components onto the OPS baseplate is described in Section 6.5.

6.2 - Diagnostic Substrate

Numerous components and modules must be assembled and accurately aligned within the interconnect system. To do so and to characterize the alignment accuracy of these elements, it was necessary to develop a diagnostic substrate (shown in Figure 6.1). The diagnostic substrate consists of a chrome mask that is lithographically deposited on a substrate with dimensions identical to that used for the fabrication of the lenslet array. The diagnostic substrate is designed such that it can be aligned in place of either the lenslet array or the OE-VLSI chip in the different modules of the system. The features on the mask consist of different targets replicating the layout of the 512-spot array. Within the OPS module, the diagnostic substrate is used to adjust the Fourier lens' focal length (Section 6.4), for the rotational alignment of the FOG (Section 6.5), and to characterize the spot array (Section 8.2).

Figure 6.1 – CAD drawing of the diagnostic substrate

6.3 - Collimation Barrel

The first step in the assembly of the OPS module is the alignment of the collimation barrel. Two critical alignments must be performed:

- i) The centering of the fiber with the optomechanical axis of the collimation barrel.
- ii) The adjustment of the spacing between the fiber and the first collimation lens and between both lenses to obtain a collimated beam with the required waist.

6.3.1 - Fiber Alignment

The alignment technique for the fiber receptacle has been described in Section 5.4.2. The fiber receptacle is placed in contact with the stopper of the collimation barrel and four screws are driven against the chamfered edge to hold the receptacle in place. To adjust the fiber receptacle's position, the fiber is inserted into the receptacle and the collimation barrel is deposited on the rods of an OPS baseplate. The core and the cladding of the fiber are then magnified and imaged on a CCD camera.

When a small amount of light is coupled into the fiber, the initial position of the fiber core on the CCD camera can easily be identified. The pixel's coordinates for both the x and y axes are then noted. By measuring the position of the fiber core in four different instances (the barrel being rotated by 90° between each measurement), we can evaluate the alignment accuracy of the fiber with respect to the optomechanical axis of the collimation barrel. The underlying principle behind this procedure is as follows: if the diameter of the collimation barrel is perfectly circular and if the fiber core is perfectly centered, the position of the fiber core on the CCD camera will be the same for all four measurements. Given that this situation is unlikely to be the case, the screws are adjusted to further center the fiber until a minimum deviation is achieved between the four measurements. The resulting centering accuracy for the four collimation barrels is shown in Table 6.1. To obtain the deviation value in microns, the CCD camera was calibrated using the known value of the fiber cladding's diameter, which is $125\text{ }\mu\text{m}$. The measured cladding diameter on the CCD camera was 175 pixels, thus $175\text{ pix} = 125\text{ }\mu\text{m}$. An analysis of the numbers in the " Δ " column indicates that the worst alignment was obtained in the second case, where the fiber is within $5\text{ }\mu\text{m}$ of the ideal position. The repeatability of the fiber insertion in the fiber receptacle was calculated by inserting and removing the fiber five times and performing the above measurements between each insertion. The repeatability is excellent since the displacement of the fiber between its removal and reinsertion is within $1\text{ }\mu\text{m}$.

Table 6.1 - Measurements of the accuracy of the fiber centering within the barrel (all values are ± 1)

Collimation barrel	0° (pix)	90° (pix)	180° (pix)	270° (pix)	Δ (pix)	Δ (μm)
1	$x = 307$ $y = 231$	$x = 309$ $y = 224$	$x = 307$ $y = 222$	$x = 300$ $y = 222$	$\Delta x = 9$ $\Delta y = 9$	$\Delta x = 6$ $\Delta y = 6$
2	$x = 463$ $y = 300$	$x = 462$ $y = 302$	$x = 472$ $y = 303$	$x = 465$ $y = 294$	$\Delta x = 10$ $\Delta y = 9$	$\Delta x = 7$ $\Delta y = 6$
3	$x = 325$ $y = 248$	$x = 324$ $y = 238$	$x = 320$ $y = 247$	$x = 322$ $y = 243$	$\Delta x = 5$ $\Delta y = 10$	$\Delta x = 4$ $\Delta y = 7$
4	$x = 196$ $y = 207$	$x = 195$ $y = 206$	$x = 195$ $y = 203$	$x = 189$ $y = 206$	$\Delta x = 7$ $\Delta y = 4$	$\Delta x = 5$ $\Delta y = 3$

6.3.2 - Collimating Lenses Alignment

Once the fiber receptacle has been centered, the design requires that the positions of the collimating lenses be adjusted to produce a collimated beam having a waist between $610\ \mu\text{m} < \omega_{CB} < 640\ \mu\text{m}$ in both x and y (the fiber mode field diameter is different for each axis). However, it was found that the size of the beam waist needed to be slightly larger than the theoretical value, that is, between $640\ \mu\text{m} < \omega_{CB} < 670\ \mu\text{m}$, to produce the required spot size ($13.1\ \mu\text{m}$) at the modulators. This need can be explained by the tolerance on the focal length of different components in the OPS module and the optical interconnect, and by variations of mode-field diameters for different fibers.

It was noted that the beam at the output of the collimation barrel had a small angular deviation with respect to the optomechanical axis of the barrel. This deviation can be attributed to the sliding-fit clearance required for the insertion of the cells into the collimation barrel, resulting in the lenses not being perfectly centered on the optical axis. However, this angular deviation can be reduced to less than 0.01° by a slight adjustment of the position of the fiber receptacle to compensate for this misalignment.

6.4 - Adjustment of the Fourier Lens Focal Length

The second step of the OPS module assembly consists of adjusting the focal length of the Fourier lens to produce a spot array with the required pitch. To do so requires that the diagnostic mask be mounted on a cell by use of the same technique as that employed for the alignment of the lenslet array (see Subsection 5.B). Positioning the collimation barrel, the FOG, the Fourier lens, and the diagnostic mask on the OPS baseplate allows the spot array to be observed on the diagnostic mask. The focal length of the Fourier lens is then adjusted to align the spot array onto the markers, ensuring that the required pitch is obtained.

6.5 - Alignment of the Components onto the OPS Baseplate

After all the collimation barrels and Fourier lenses have been adjusted it is possible to align an OPS module in less than 15 min, as follows. When the cells are deposited onto the rods in the baseplate, four out of six mechanical degrees of freedom are constrained: Only the roll and the longitudinal position of the elements need to be adjusted. Given that a collimated beam is output from the collimation barrel, the longitudinal alignment of only three elements is critical:

- i) The FOG must be positioned at the front focal point of the Fourier lens.
- ii) The distance between the Fourier lens and the OPS lenslet array (LA_1) must be equal to the back focal length of the Fourier lens plus f_{LA} such that the output beams of the OPS module are collimated.
- iii) The OPS lenslet array (LA_1) must be positioned at a distance of $f_{LA} \pm 500 \mu\text{m}$ from the PMG after the OPS baseplate is inserted into the interconnect baseplate (to preserve the interconnect system telecentricity).

Furthermore, the roll of only three elements needs to be adjusted:

- i) The roll of the FOG must be adjusted so that the spot array at the output of the OPS module is rotationally aligned with the PMG and the interconnect system.
- ii) The roll of lenslet array LA_1 must be adjusted so that it is rotationally aligned with the spot array at the output of the Fourier lens.
- iii) The roll of the QWP must be adjusted to circularize the light polarization to maximize power transfer to the interconnect system.

The first step in the alignment of an OPS module is to position the Fourier lens onto the rods. Given the optomechanical design and given that the back focal length of the Fourier lens and f_{LA} are known, the position of the Fourier lens with respect to the end of the OPS baseplate can be calculated. The Fourier lens is then positioned by hand to within $200 \mu\text{m}$ of its ideal position.

Next, the position of the FOG is adjusted by the imaging of the grating through the Fourier lens on a screen placed approximately 50 cm from the Fourier lens. Only when the FOG is at the front focal point of the Fourier lens will a clear image of the grating be visible on the screen. Using this technique allows the position of the FOG to be estimated to be aligned to within 50 μm of the Fourier lens's front focal point. To adjust the roll of the FOG, a diagnostic substrate is accurately aligned to precisely machined markers on a rectangular holder. The holder is then positioned on the rods of the OPS baseplate such that the alignment features are located at the back focal point of the Fourier lens. Because of the flat base of the rectangular holder, the alignment markers provide a reference to perform the rotational alignment of the FOG. The FOG is rotated by hand and its rotational alignment is within 0.5°.

Next, lenslet array LA_1 is deposited onto the baseplate and rotated such that its columns of minilenses are parallel to the incident beams. This alignment is performed with the use of a mirror positioned about 15 cm after the LA_1 such that the beams are reflected onto the lenslet holder. The LA_1 holder is then rotated until the reflected beams are parallel to those at the output of the LA_1 (see Figure 6.2). Because of the imperfect alignment of the LA_1 with respect to the mechanical center of its cell, the RPP is then rotated such that each spot of the array is aligned in the center of a minilens. The longitudinal position of LA_1 is then adjusted to collimate the beam by minimization of the divergence angle of the spot array.

Figure 6.2 – Photograph of the reflected beams during the LA_1 rotational alignment

Finally, the assembly of the OPS module is completed by the insertion of the QWP into the baseplate and the adjustment of its roll such that the power transmission into the interconnect is maximized. This step is performed after the OPS baseplate has been mounted on the interconnect baseplate. A photograph of an assembled OPS module is shown in Figure 6.3.

Figure 6.3 – Photograph of an assembled OPS module

6.6 - Summary

Different alignment techniques were developed and incorporated into the design of the OPS module. These techniques together with the simplicity of the OPS module's optical and optomechanical designs significantly facilitated its assembly. Furthermore, because of its modularity, the collimation barrel only needs to be aligned once and it can easily be inserted and removed from the OPS module. A full characterization of the OPS module is provided in Chapter 8.

6.7 - References

No references for this chapter.

Chapter 7 - Insertion of the OPS Module in the Interconnect Baseplate

7.1 - Introduction

The most critical part of the optomechanical design for the OPS module is its attachment to the interconnect baseplate. To better understand the attachment technique and the packaging of the second stage of the array-generator system, an overview of the interconnect baseplate is presented in Section 7.2. The mounting technique is then described in Section 7.3, and the characterization of the repeatability of the insertion is presented in Section 7.4.

7.2 - Overview of the Interconnect Baseplate

The interconnect baseplate is designed as the optomechanical reference to which all modules are aligned (see Figure 2). For simplicity and ease of assembly, the modules are passively aligned by use of rods, holes, and dowel pins. The beam-combination and the beam-relay modules are packaged in the slot of the interconnect baseplate, whereas the OPS and the chip modules are mounted on the baseplate. The technique for the alignment of the PMG (which is part of the beam-combination module) on the interconnect baseplate is shown in Figure 7.1. The PMG substrate is precisely diced, and its edges are placed against three dowel pins. A clamp is then used to hold the module in place. The lenslet array in the second stage of the array generator (LA₂) is packaged in the chip module. This chip module is mounted on the interconnect baseplate by the mating of the chip-module holder to two precision-ground dowel pins. This technique is described further in reference 1.

7.3 - OPS Baseplate Mounting Technique

Each OPS module must be inserted at 90° to the plane that contains the optical axis of the ring interconnect. The attachment of the OPS module to the optical interconnect is achieved by the mating of the rods of the OPS baseplate to holes machined in the

interconnect baseplate. The holes have the same specifications as that of the rod-alignment holder (see Section 5.3): they are designed to provide a tight sliding-fit clearance for the rods and machined to within 5 μm of the design value. The measured rod diameter is 4.990 ± 0.002 mm, whereas the specification for the diameter of the holes is $5.004 + 0.012/-0.000$ mm.

The rods together with the flat surfaces of the baseplates provide a kinematic reference that constrains angular movement (both rotation and tilt). Furthermore, because the optical axis of the OPS module is defined by the two rods, any inaccuracy in the position of the OPS's optical axis is limited to the relative positioning error of the holes in the interconnect baseplate to the other features on the interconnect baseplate. Finally, the OPS baseplate is fixed in place with screws in oversized holes. The mounting of the OPS baseplate to the interconnect baseplate is shown in Figure 7.1.

Figure 7.1 – Schematic diagram of the OPS module insertion in the interconnect baseplate

7.4 - Kinematic-Alignment-Mechanism Characterization

To validate the design approach for the mounting of the OPS module, a prototype baseplate was fabricated. A diagnostic substrate was aligned on the baseplate in place of the PMG and by use of the same technique. The OPS baseplate was removed, reinserted and secured in place 30 times. For every extraction-insertion cycle, the lateral and the angular misalignments of the beam array with respect to the diagnostic substrate was noted. The results are shown in Figure 7.2 whereas the average misalignment values are shown in Table 7.1. The average lateral misalignment is $154\text{ }\mu\text{m}$ in x and $123\text{ }\mu\text{m}$ in y , whereas the angular misalignment is 0.171° in x and 0.036° in y . The position and the angle of incidence of the beams on the substrate can be adjusted by use of the RRP such that the small misalignments can be eliminated.

Figure 7.2 – Characterization of the OPS baseplate insertion misalignment
Lateral misalignment (μm); (b) Angular misalignment ($^\circ$)

Table 7.1 – Average misalignment for the OPS baseplate insertion

Misalignment	Average value
x lateral	$154 \pm 3\text{ }\mu\text{m}$
y lateral	$123 \pm 3\text{ }\mu\text{m}$
x angular	$0.171 \pm 0.001^\circ$
y angular	$0.036 \pm 0.001^\circ$

The repeatability of the insertion can be characterized by a comparison of the misalignment standard deviations with the alignment tolerance between the OPS module and the optical interconnect for a 1% power loss. These tolerances, which were presented in Table 2.2, are 55 μm (lateral) and 0.05° (angular). The normalized misalignments are presented in Figure 7.3. The standard deviation for the lateral misalignment is $\sigma_x = 5.8 \mu\text{m}$ and $\sigma_y = 4.1 \mu\text{m}$, whereas it is of $\sigma_x = 0.004^\circ$ and $\sigma_y = 0.006^\circ$ for the angular misalignment. The results indicate that, after the RRP has been adjusted to align the beams onto the modulators, the OPS baseplate can be removed and passively reinserted such that all the beams remain aligned on the chip.

Figure 7.3 – Normalized baseplate insertion misalignment
 (a) Lateral misalignment (μm); (b) Angular misalignment ($^\circ$)

Table 7.2 – Standard deviation of the repeatability for the OPS baseplate insertion

Repeatability	Standard deviation
x lateral	5.8 μm
y lateral	4.1 μm
x angular	0.004°
y angular	0.006°

7.5 - Summary

The main objective of the optomechanical design for the OPS module was to provide a kinematic alignment system to mount the OPS baseplate onto the interconnect baseplate. The results presented in this chapter confirm the validity of the design. Although the array is slightly offset from the modulators and need to be aligned when the OPS module is first inserted, no readjustment is required when the module is removed and reinserted.

7.6 - References

- [1] M. H. Ayliffe, D. Kabal, P. Khurana, F. Lacroix, A. G. Kirk, F. A. P. Tooley, and D. V. Plant, "Electrical, thermal and optomechanical packaging of large 2D optoelectronic device arrays for free-space optical interconnects," *J. Opt. A: Pure Applied. Optics*, Vol. 1, No. 2, p. 267-271, March 1999.

Chapter 8 - Characterization

8.1 - Introduction

Four OPS modules were implemented and a detailed characterization of the performance was carried out. The goal was to obtain statistical information on the reproducibility of the design and implementation. The results are presented in the following subsections.

8.2 - Spots and the Spot Array

There are three main parameters that must be characterized for the spot array: The spot size, the array pitch, and the array power uniformity. The measured values of these parameters for all four OPS modules are shown in Table 8.1, and a photograph of the spot array at the modulators is shown in Figure 8.1. Because the system is telecentric, the spot size at the modulators is the same as that at the output of the Fourier lens. For this reason a beam profiler (Photon BeamScan model #0180) mounted on a micrometer stage was used to measure the spot size at the back focal point of the Fourier lens. The average value is $13.2\text{ }\mu\text{m}$, while the worst-case measurement ($13.7\text{ }\mu\text{m}$) is within $0.6\text{ }\mu\text{m}$ of the design value. The spot profile obtained with the beam profiler for the OPS 2 is shown in Figure 8.2.

Table 8.1 – Characterization results for the four OPS modules

	OPS 1	OPS 2	OPS 3	OPS 4
Spot pitch (μm)	1601.2 ± 0.4 $\times 801.2 \pm 0.2$	1602.0 ± 0.4 $\times 800.7 \pm 0.2$	1602.2 ± 0.4 $\times 801.5 \pm 0.2$	1602.4 ± 0.4 $\times 799.7 \pm 0.2$
Fourier lens spot size (μm)	$\omega_x = 13.4 \pm 0.1$ $\omega_y = 13.1 \pm 0.1$	$\omega_x = 13.0 \pm 0.1$ $\omega_y = 12.9 \pm 0.1$	$\omega_x = 13.0 \pm 0.1$ $\omega_y = 12.9 \pm 0.1$	$\omega_x = 13.7 \pm 0.1$ $\omega_y = 13.4 \pm 0.1$
Fan-out grating nonuniformity	$12 \pm 1\%$	$11 \pm 1\%$	$11 \pm 1\%$	$11 \pm 1\%$
Patterned mirror nonuniformity	$3 \pm 1\%$	$4 \pm 1\%$	$4 \pm 1\%$	$4 \pm 1\%$

Figure 8.1 – Photograph of the 512 spot array

Figure 8.2 – Spot profile for the OPS 2: (a) in x ; (b) in y

The pitch of the 4×8 array was measured by means of placing a mask at the back focal point of the Fourier lens. The positions of the four outer spots were monitored on the mask, as shown in Figure 8.3. The pitch of the array was derived by measurement of the spot displacements from the markers and then distribution of the error over the entire

array. This technique allows the evaluation of the worst-case spot pitch because displacements of the outer spots are largest as a result of distortion and aberrations. This also explains the fact that the steeper pitch (1600 μm) is not exactly twice as large as the lesser one (800 μm). The worst pitch, which is $1602.2 \pm 0.4 \mu\text{m} \times 801.5 \pm 0.2 \mu\text{m}$ (OPS 3), is within the tolerance of the system. A similar technique was utilized to characterize the spot pitch of the 4×4 array. An OPS module was inserted into the interconnect baseplate, and the pitch of the outermost cluster was measured. The result was $89.1 \pm 0.2 \mu\text{m} \times 89.1 \pm 0.2 \mu\text{m}$, which is excellent.

Figure 8.3 – Photograph of the 4×8 spot array on the diagnostic mask substrate

A common metric for quantifying the uniformity of FOG's is to consider that the power distribution in the array approximates a normal distribution and to calculate the standard deviation. Using this metric showed the measured nonuniformity for the 4×8 array produced by the FOG's to be 12%. However, because the system employs differential encoding and because pairs of beams illuminating the modulators and the detectors are created at the PMG, these beams will have the same relative dc offset. Thus the FOG's nonuniformity should not result in any impact on the performance of the system. On the other hand, the uniformity of the PMG's is more critical than that of the FOG's. The average measured nonuniformity for the 4×4 array generator is 4%, and no significant zero-order beam is present in any of the spot arrays. Thus pairs of beams in a data channel will have almost identical power at the modulators. Note that the impact of the array nonuniformity on the performance of the system is not within the scope of this thesis.

8.3 - Power Budget and Efficiency

Throughput efficiency measurements were performed on each of the optical elements of the array-generation system with a precision of $\pm 1\%$. The values are presented in Table 8.2 and compared to the optimistic and pessimistic predictions. The pessimistic diffractive efficiency value for the 8 level DOE's include the effect of possible fabrication errors (mask alignment and etch depth errors) [1], and was assumed to be 5% less than the theoretical value. All the measurements are within the optimistic and pessimistic prediction range, except for the FOG and the PMG. The low efficiency and high nonuniformity of the FOG are most probably attributable to the difficulty of designing an element that produces such a large diffraction angle. The low efficiency of the PMG is probably attributable to fabrication errors. The final column in Table 8.2 shows the cumulative throughput efficiency based on the measured data from column 4. It is shown that a cumulative throughput between 39.1% (pessimistic) and 47.9% (optimistic) was expected. However, due to the low diffraction efficiency of the FOG, the measured cumulative throughput is below the pessimistic value and was measured to

be $33 \pm 5\%$. Finally, note that this power budget does not include the components of the interconnect system that are not utilized in the array generation system.

Table 8.2 – Efficiency prediction and characterization for the array-generation system

Optical Component	Optimistic prediction	Pessimistic prediction	Measured value	Cumulative efficiency
Collimation barrel	99.0%	98.0%	$99 \pm 1\%$	$99 \pm 1\%$
Risley prism pair	99.0%	98.0%	$99 \pm 1\%$	$98 \pm 2\%$
Quarter-wave plate	99.5%	99.0%	$99 \pm 1\%$	$97 \pm 2\%$
Fan-out grating (diffraction efficiency)	82.0%	82.0%	$70 \pm 2\%$	$68 \pm 4\%$
Fan-out grating (reflection loss)	92.2%	92.2%		
Fourier lens	97.5%	95.1%	$95 \pm 1\%$	$65 \pm 4\%$
Minilens (diffraction efficiency)	95.0%	90.0%	$84 \pm 2\%$	$54 \pm 5\%$
Minilens (reflection loss)	92.2%	92.2%		
Patterned-mirror grating (diffraction efficiency)	95.0%	90.0%	$72 \pm 2\%$	$39 \pm 5\%$
Patterned-mirror grating (reflection loss)	92.2%	92.2%		
Minilens (diffraction efficiency)	95.0%	90.0%	$84 \pm 2\%$	$33 \pm 5\%$
Minilens (reflection loss)	92.2%	92.2%		
Total efficiency	47.9%	39.1%	$33 \pm 5\%$	$33 \pm 5\%$

8.4 - Summary

The characterization results presented in this chapter demonstrate that all four OPS modules perform within the tolerances required for the system to operate. This suggests that the design is robust as it can be implemented numerous times successfully. The power efficiency for the system has been compared to the optimistic and pessimistic predictions. Although the nonuniformity of the FOG and PMG are higher than expected, this should not result in any impact on the performance of the system.

8.5 - References

- [1] J. M. Miller, M. R. Taghizadeh, J. Turunen and N. Ross, "Multilevel-grating array generators: fabrication error analysis and experiments," *Applied Optics*, Vol. 32, No. 14, p. 2519-2525, 1993.

Chapter 9 - Conclusion

9.1 - Discussion

Free-space optical interconnects represent a possible solution to circumvent some of the connectivity problems being encountered in digital processing systems. This is especially true at the backplane level where the limitations have even more severe performance consequences. The optical backplane system demonstrator, presented in Chapter 2 of this thesis, is a modulator-based free-space optical interconnect and thus requires that a readout array of beams be generated off chip to illuminate the modulators.

This thesis has focused on the design, the implementation and the characterization of a spot-array generator to drive the array of 512 modulators used in the demonstrator system. Before undertaking the design of the array generator, an analysis of the optical interconnect was performed to develop stringent requirements for the spot array and for the optomechanics. The optical design of the array generator was then developed in conjunction with the packaging strategy such that all the requirements would be met. The requirements together with the measured values for the implemented system are again presented in Table 9.1. The resulting implementation includes several interesting characteristics that will now be discussed.

First, because producing the entire array of 512 beams using a single diffractive optical element would have represented a significant design challenge, it was decided to utilize a cascaded array-generation system. Although this technique involves an additional alignment step, it has the advantage of producing a spot array with higher uniformity than that produced by a single Fourier plane array generator. The cascaded array-generation system was successfully implemented to obtain the large fan-out required.

Second, the combination of the optical and optomechanical designs resulted in a robust, compact, easy-to-assemble and modular implementation. The advantage for using a modular implementation is that the module can be pre-aligned and then mounted onto the

system. This also significantly simplifies the alignment of the system demonstrator. These characteristics of the OPS module are important for moving towards commercially viable implementations of optical interconnects.

Table 9.1 – Optical requirements for the externally generated spot array

Optical requirements	Requirement value	Measured value
Wavelength	852.0 nm	852.0 ± 0.1 nm
4 × 8 array of cluster pitch	1600 × 800 μ m	1602.2 ± 0.4 μ m × 801.5 ± 0.2 μ m *
4 × 4 cluster array pitch	90 × 90 μ m	89.1 ± 0.2 μ m × 89.1 ± 0.2 μ m
Beam waist at modulators ($1/e^2$)	13.1 μ m	$\omega_x = 13.7 \pm 0.1$ μ m * $\omega_y = 13.4 \pm 0.1$ μ m *
Input polarization linearity	100:1	1500:1
Optomechanical Requirements for a 1% power loss for the OPS module		
	Requirement	Measured
Roll around the optical axis	45 arc minutes (0.75°)	< 6 arc minutes (0.1°)
Lateral alignment repeatability	55 μ m	$\sigma_x = 5.8$ μ m $\sigma_y = 4.1$ μ m
Angular alignment repeatability	3 arc minutes (0.05°)	$\sigma_x = 0.004^\circ$ $\sigma_y = 0.006^\circ$

* Worst case out of four implementations

Third, the optical axis of the OPS module was aligned to that of the interconnect system at 90°. The rods and the flat surface of the OPS baseplate provided a kinematic reference for the alignment of the two optical axes. The final adjustment was realized by the rotation of the RPP such that the array would be perfectly aligned to the modulators on the OE-VLSI chip. Again, the modular approach simplifies the alignment and assembly of the system demonstrator.

Finally, the main objective for the optomechanical design of the OPS module was to develop a mechanism allowing that the module be removed and reinserted without requiring any realignment. The measured values for the standard deviation of the lateral and angular repeatability are, respectively, $\sigma_x = 5.8 \mu\text{m}$, $\sigma_y = 4.1 \mu\text{m}$ and $\sigma_x = 0.004^\circ$, $\sigma_y = 0.006^\circ$. A comparison of the standard deviation with the requirements for a 1% power loss in the optical interconnect throughput ($55 \mu\text{m}$, 0.05°) leads to the conclusion that the insertion of the module is repeatable.

To conclude this discussion, it should be noted that light was successfully routed from the modulators to the detectors in the optical interconnect [1], thus further demonstrating that the requirements for the OPS were satisfied. Figure 9.1 is a photograph of the 1024 beams resulting from the combination of an array routed from a previous stage with the array produced by the OPS module for the current stage. Note that the distortion at the extremities is due to the optical system utilized to image the array onto the CCD camera.

Figure 9.1 – Photograph of the 1024 beams

9.2 - References

- [1] F. Lacroix, B. Robertson, M. H. Ayliffe, E. Bernier, F. A. P. Tooley, M. Châteauneuf, D. V. Plant, and A. G. Kirk, "Design and Implementation of a Four-Stage Clustered Free-Space Optical Interconnect," *Proceedings of the SPIE*, Vol. 3490, p. 107-110, 1998.

Appendix A - Copy of the Paper to be Published by Applied Optics

The following manuscript has been accepted for publication in a special issue of Applied Optics on "Optics In Computing":

D. F.-Brosseau, F. Lacroix, M. H. Ayliffe, E. Bernier, B. Robertson, F. A. P. Tooley, D. V. Plant, and A. G. Kirk, "Design, implementation and characterization of a kinematically aligned, cascaded spot-array generator for a modulator-based free-space optical interconnect," Applied Optics, Vol. 39, No. 5, p. 733-745, 10 February 2000.

The contributions of the different authors, which were described in the acknowledgements, and are now reiterated:

First, the project was realized under the supervision of Professors Andrew Kirk, David Plant and Frank Tooley. Second, the optical interconnect system was originally designed by Brian Robertson. Third, the implementation of the system was divided into sub-projects under the responsibility of the following persons, which I would like to thank:

- Frédéric Lacroix for the assembly of the interconnect system (beam-combination and beam-relay module) and the measurement of the diffractive optical elements' efficiency (which was done with the help of Marc Châteauneuf);
- Michael Ayliffe for the design and assembly of the chip module, the specifications of the diffractive optical elements, and the design of the diagnostic substrate;
- Eric Bernier for the design of the interconnect baseplate and the characterization of the OPS module insertion into the interconnect baseplate (with the help of Michael Ayliffe);
- David Rolston for the design of the optoelectronic VLSI chip.

Although I was responsible for the design and implementation of the OPS module, I would like to thank all the above individuals for their help and suggestions.

ABSTRACT

Design, implementation, and characterization of a kinematically aligned, cascaded spot-array generator for a modulator-based free-space optical interconnect

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The design and the implementation of a modular spot-array generator for a modulator-based free-space optical interconnect is presented. Two cascaded diffractive optical elements produce 4×8 clusters on a $1600 \times 800 \mu\text{m}$ pitch, where each cluster is a 4×4 array of $(1/e^2)$ $13.1\text{-}\mu\text{m}$ -radius spots on a $90\text{-}\mu\text{m}$ pitch. The spot-array generator is kinematically aligned to the interconnect system such that no realignment is necessary between removal and reinsertion. Characterization results are presented.

OCIS Codes:

200.2610 Free-space digital optics

200.4650 Optical interconnects

050.0050 Diffraction and gratings

1. Introduction

Two-dimensional (2-D) free-space optical interconnects represent a possible solution for alleviating some of the interconnection bottlenecks currently experienced by high-performance electronic systems [1]. The two most widely investigated optoelectronic technologies for free-space optical data transmission are multiple-quantum-well (MQW) modulators and arrays of vertical-cavity surface-emitting lasers (VCSEL's) [2-4]. VCSEL's have many interesting optical characteristics [5-6] and significant progress in their development such as their integration to complementary metal-oxide semiconductor (CMOS) technology have recently been achieved [7]. However, the design of compact optical interconnects that possess a large number of optical channels would require large arrays ($>32 \times 32$) of single-mode VCSEL's demonstrating both good uniformity and stability that are hybridized to CMOS integrated circuits. At the time the research reported here was conducted such devices were not yet available. Furthermore, the current threshold uniformity and the thermal management of large VCSEL arrays remains a challenge.

In contrast, large arrays of MQW modulator devices flip-chip bonded to CMOS's with excellent characteristics have already been demonstrated [8]. This proven technology has been employed by many research groups for the realization of free-space optical interconnects [9-11]. Recently, a modulator-based free-space optical interconnect was developed for optical backplane applications [12]. The system uses a minichannel-based interconnection scheme [13] in which a telecentric lenslet arrangement allows multiple signal beams to be relayed through each minichannel. A clustered-window geometry in

which optoelectronic devices are physically grouped in a 4×4 matrix about the axis of each minichannel is employed. There are 8×8 minichannels of such 4×4 cluster, which results in a system with 1024 optical channels. Modulator based systems require that the modulators be illuminated with a 2-D array of uniform cw readout beams. This requirement motivates the need to develop a suitable spot-array generator. In this paper the design and the implementation of an array generator for such a clustered optical interconnect is described.

Although numerous techniques exist for generating spot arrays [14] most free-space optical interconnects rely on the Fourier plane array-generation technique [14-18]. To read out the logical state of the modulators, it is necessary for the system described here to have an array of 4×8 clusters on a $1600 \mu\text{m} \times 800 \mu\text{m}$ pitch in which each cluster is an array of 4×4 spots on a $90\text{-}\mu\text{m}$ pitch (see Fig. 1). The geometry of the clustered spot array can easily be implemented by the cascading of two Fourier plane array generators. A cascaded implementation possesses the advantage of producing a spot array with higher uniformity than that produced by a single Fourier plane array generator [19].

Spot-array generators have been implemented by use of different techniques and packaging approaches [9-11,20]. However, not much emphasis has been placed on developing an array-generation system that is compact and modular and that can be aligned kinematically with the optical interconnect. It is advantageous for scalable multistage systems if optical array generators are designed as separate modules that are prealigned and then mounted on the system. Furthermore, it is important that such a module be easy to assemble. Finally, to facilitate test and repair, it is necessary that the

module be designed such that it can be unmounted and remounted on the system without realignment. All these concerns have been addressed by the design of the spot-array generator for our proposed system.

The format of this paper is as follows: Section 2 presents a short overview of the optical interconnect system. The optical and the optomechanical requirements for the spot-array generator are introduced in Section 3. Section 4 presents the optical design of the cascaded array-generator system, whereas the optomechanical design is presented in Section 5. The assembly and the alignment procedures of the optical-power-supply (OPS) module is discussed in Section 6. Section 7 describes the kinematic-alignment mechanism of the array generator to the optical interconnect. Finally, Section 8 presents characterization results.

2. Optical Interconnect Overview

The design of the optical interconnect was described in Ref. 12. This system, which interconnects optoelectronic-VLSI (OE-VLSI) chips in a unidirectional ring (see Fig. 2), is designed to be scalable (to an arbitrary number of boards), modular (to allow easy assembly and maintenance), compact, robust, and misalignment tolerant. The OE-VLSI chips are based on GaAs/AlGaAs MQW electroabsorption modulators and p-i-(MQW)-n detectors, which are flip-chip bonded to CMOS electronics, that operate at 852 nm for optical input and output. A dual-rail data-encoding scheme is used such that two modulator devices are used to encode data differentially. A point-to-point link is implemented between the modulators of one OE-VLSI chip and the detectors of the subsequent chip (see Fig. 3). The minichannel-based relay system requires that arrays of

4×4 signal beams be transmitted simultaneously through each of the 8×8 array of symmetric $4f$ telecentric relays. The 8×8 arrays are designed with alternating columns of modulator and detector windows, and the resulting window density is 2500 windows/cm². Optical data transmission is achieved by the modulation of an externally generated spot array. The optically encoded data is then routed from one stage to the next by means of polarization optics and patterned mirrors. Polarizing beam splitters are used either to reflect or transmit linearly polarized light, depending on its orientation relative to the plane of incidence. The state of polarization is changed from linear to circular and vice versa by use of quarter-wave plates (QWP's) that have their slow axes oriented at 45°.

The optical interconnect is implemented by use of a modular approach (see Fig. 3). This approach reduces the component count and the number of mechanical degrees of freedom to be aligned in the interconnect baseplate, which relaxes alignment tolerances [21]. Descriptions and assemblies techniques for the beam-combination, beam-relay and chip modules were already published [21-23].

3. Spot-Array Generator Requirements

A. Optical Requirements

Several design characteristics are required for the spot array. First, the design of the modulators, the detectors, and the diffractive optical elements were specified for an operation wavelength of 852.0 nm. Furthermore, the optical source of the system should provide linearly polarized light with an extinction ratio that is greater than 100:1 so that

the loss in the interconnect's power throughput is less than 1%. Second, the layout of the spot array must be the same as that of the modulators on the OE-VLSI chip, as shown in Fig. 1. Third, for compatibility with the interconnect optics the interconnect design requires that the $1/e^2$ spot radius at the modulators and the detectors be $13.1\text{ }\mu\text{m}$ [12]. Finally, the field curvature of the spot array should be minimized, whereas the power uniformity across the entire array should be maximized. Table 1 summarizes these requirements and presents the measured values of the implemented system (these characterization results are discussed in Section 8).

B. Optomechanical Requirements

There are two main issues that must be addressed by the design of the optomechanics for the OPS module. First, the optomechanical support must ensure that all elements remain stable and well aligned to a common optical axis, while at the same time allowing them to be easily removed, replaced, and repositioned. Second, the optomechanical design must include a technique for mounting the OPS module onto the interconnect baseplate. The optical interconnect design requires that the optical axis of the OPS module be aligned at 90° to that of the interconnect system (as shown in Fig. 3). To allow for simple replacement and repair procedures, it is also desirable for a kinematic-mounting mechanism to be developed such that the OPS module can be unmounted and remounted without requiring any realignment. Finally, the optomechanical design should be compact, robust, and easy to assemble, while minimizing cost.

An analysis of the tolerances for the alignment of the OPS module to the interconnect optics was presented in Ref. 21. The requirements listed in the second section of Table 1

represent the alignment tolerances associated with a 1% loss in the optical power throughput through the interconnect. Because this metric is conservative, the system can still operate if these tolerance specifications are not met. However, a further increase in system misalignment will ultimately translate into lower operating speeds or larger bit error rates.

4. Optical Design

A. Design Choices

Various possibilities were examined for the design of the array generator. The most obvious solution would be to generate the entire spot array with a single diffractive optical element and a Fourier lens. However, to produce the required array of 512 beams and achieve good uniformity would require a diffractive optical element of at least 2048×2048 pixels [24], which would represent a significant design challenge. Another possibility would be to use an $8f$ optical system with two array-generation stages consisting of a 4×8 generator and a single 4×4 array generator with three identical Fourier lenses (as demonstrated in Ref. 16). However, this scheme represents a bulky system that does not scale well. Furthermore, because the beam divergence required at the modulator array is determined by the design of the interconnection system and because the minilenses that are used to route light through the system are already in place in front of the modulators, it was desirable to also use those lenses as part of the array-generation system. This decision led to the design described in Subsection 4.B.

B. Cascaded Array-Generation System Design

A schematic drawing of the array-generation system design is shown in Fig. 4. Two Fourier plane array generators are cascaded to produce the required array of 512 beams.

The first stage produces an array of 4×8 beams on a $1600 \times 800 \mu\text{m}$ pitch, which corresponds to the layout of modulator clusters on the OE-VLSI chip. Each of these beams is then fanned out into an array of 4×4 spots on a $90\text{-}\mu\text{m}$ pitch. The Fourier plane array generators are computer-generated holograms implemented as a binary-level (4×8 fan-out) and a multiple-level (4×4 fan-out) phase grating.

There are four lens transformations in the array-generation system:

- i) The collimation of the beam emitted from the fiber.
- ii) The focusing of the collimated beam at the output of the Fourier lens.
- iii) The collimation of the beam at the output of the OPS module.
- iv) The focusing of the collimated beam onto the modulators.

With the Gaussian beam-propagation model it is possible to calculate the required beam waists in the array-generation system. Because of the telecentricity of the system, all waists are located at the focal points of the different lenses. Given a lens of focal length f with an input beam waist of ω_0 , the output beam waist is approximately equal to

$$\omega_0' \approx \frac{\lambda}{\pi \omega_0} f \quad (1)$$

given that $2z_0 \gg f$ for all four lens transformations (z_0 is the Rayleigh range) [25]. The calculated beam waists for all lens transformations are shown in Fig. 4. Note that, because the system is telecentric, the beam waist at the focus of the Fourier lens ω_{F1} is the

same as that at the modulators ω_{MOD} . The fiber mode-field diameter (or $2\omega_{fiber}$) was measured to be $6.5 \mu\text{m}$ in x and $6.2 \mu\text{m}$ in y . The effective focal length of the collimating lens that is required to produce a beam with the required waist ω_{F1} is $f_{C1} = 7.35 \text{ mm}$.

C. Optical-Power-Supply Module Optical Design

The OPS module implements the first stage of the array-generation system. Because the module is assembled and characterized separately, a separate set of requirements was developed for the output beams of the OPS module. It is necessary to produce an array of 4×8 collimated beams with a waist of $\omega_{OPS} = 176.0 \mu\text{m}$ on a $1600 \times 800 \mu\text{m}$ pitch. The optical design should provide a means of laterally translating the beams by $\pm 300 \mu\text{m}$ such that they can be aligned with the OE-VLSI chip after the OPS module is inserted into the interconnect baseplate. Finally, the state of polarization of the light must be right-hand circular for it to be routed properly in the interconnect system. The objective for the OPS module optical design is to meet all these requirements while reducing the optomechanical complexity to a minimum. To do so, it is necessary that a number of optical and optomechanical degrees of freedom be incorporated in the design of the OPS module. These design items are presented in Table 2.

A schematic diagram of the OPS module's optical design is shown in Fig. 5. The light is delivered through a fiber connect (FC) PM single-mode fiber. The light output from the PM fiber shows excellent polarization characteristics and has an extinction ratio greater than 1500:1. For design simplicity it was decided to use off-the-shelf lenses to collimate the light from the PM fiber. A combination of an aspheric lens ($f = 6.26 \text{ mm}$) and a negative achromatic lens ($f = -20.14 \text{ mm}$) was chosen to reduce aberrations. The spacing

between the lenses is variable to accommodate for variations in the divergence of the light emitted by the fiber and for deviations of the focal length ($\pm 1\%$) such that the effective focal length can be adjusted to $f_{\text{CL}} \approx 7.35$ mm. Because the light at the output of the fiber is linear and p polarized, a QWP is used to change the state of polarization to right-hand circular. The beam then passes through a 0.5° Risley prism pair (RRP) that provides a ± 330 - μm lateral adjustment of the spot array.

The fan-out grating (FOG) is a Fourier plane array generator that is placed at the waist of the collimated beam. This binary diffractive element has a period of $32\ \mu\text{m} \times 64\ \mu\text{m}$ and is designed to produce an array of 4×8 diffraction orders (odd orders only). The FOG can be rotated to align the spot array with respect to the optical axis.

The optical properties of the Fourier lens have an influence on numerous characteristics of the 4×8 spot array (see Table 2): The choice of the Fourier lens is thus an important one. A detailed description of the chosen Fourier lens can be found in Ref. [1]. The lens comprises five elements and achieves good correction for the achromatizing aberrations, such as spherical, astigmatism, and distortion. It also provides a large field size (7.7 mm), while maintaining low field curvature and distortion (f-sin θ distortion of less than 0.025% across the 20.7° field of view). The design allows the Fourier lens's focal length to be adjusted precisely to $f_{\text{FL}} = 30.00$ mm by variations of the spacing of the last element, which acts as a field flattener. This adjustment is necessary because the required focal-length control for achieving a 1- μm spot-position error is 1 part in 2000 (Ref. [1]). Finally, the optical elements are packaged in a magnetic stainless-steel barrel with an outer diameter of 25.00 mm.

The last element of the OPS Module is an array of 8×8 minilenses on an 800- μm pitch ($f_{\text{LA}} = 8.5$ mm), and it is used to collimate the beams. The minilenses used in this system all have the same design and are eight-level diffractive elements.

D. Second-Stage Optical Design

The second stage of the array-generation system (as shown in Fig. 4) consists of a FOG in combination with a lenslet array that acts as a Fourier lens. The patterned-mirror grating (PMG) consists of four FOG stripes interlaced with four metal-mirror stripes. The grating, which is an eight-level element, has a period of 161 μm and is designed to produce a 4×4 array on a 90- μm pitch when used in combination with an 8.5-mm Fourier lens. The waists of the collimated beams produced by the OPS module must be incident upon the grating, and the lenslet array must be placed at a distance f_{LA} from the PMG for each beam to be divided into the required spot array. The PMG is assembled as part of the beam-combination module [21] and packaged in the interconnect baseplate. The metal stripes are used in the interconnect to reflect data from the previous stage onto the receivers (see Fig. 3). Finally, the lenslet array is packaged as part of the chip module [22].

E. Design Modeling and Simulation

The optical design was modeled by use of a commercial ray-tracing software. The point-spread function and the Strehl ratio were calculated for the spots at the modulators. The calculations were performed for two different spots: the center spot, which is located on the optical axis (i.e. the zero order for both the FOG and the PMG), and the outer spot,

which is the farthest from the optical axis in the 512-spot array. The outer spot is located at a distance of 3878 μm from the optical axis. Because the simulation software does not allow for array propagation, an equivalent optical system was designed by the modification of the period of the gratings such that a spot is produced on the y axis at the required distance from the optical axis.

The point-spread function indicates that the center and the outer spot radii ($1/e^2$) are 13.7 μm , which is slightly larger than the Gaussian beam design value (13.1 μm). This minimal increase, which results in a spot of $3\sigma = 41.1 \mu\text{m}$, can be tolerated by the oversized modulators (50 μm) and detectors (70 μm). The Strehl ratios for the center and the outer spots are, respectively, 0.892 and 0.886. These ratios indicate that aberrations are reduced to the Rayleigh limit [26], and the system can therefore be considered to be diffraction limited. Finally, Gaussian beam-propagation simulation confirmed the calculated beam waists presented in Fig. 4.

5. Optomechanical Design of the Optical-Power-Supply Module

For addressing the optomechanical requirements presented in Subsection 2.B different packaging strategies are available. For example, a barrel assembly was employed in a previous implementation of an OPS [20]. However, it was found that the barrel assembly is not ideal for implementation for several reasons. First, the components are not easily accessible when housed in a barrel: Their insertion, removal, and repositioning are tedious and time consuming. Second, the mounting of the barrel assembly onto a baseplate lacks sufficient insertion accuracy.

The packaging strategy for the OPS module in this system consists of centering the optical components in 25.00-mm magnetic stainless-steel cells and then depositing them onto a baseplate. The baseplate is made of a rectangular slot with two precision-ground rods positioned in the corners of the slot, the rods acting as rails for the cells. Rare-earth magnets are glued onto the bottom of the slot; they constrain the cells laterally and angularly. This strategy is similar to that presented in Refs. 27 and 28 in which either a V groove or a rectangular slot was used to support the components and define two reference axes for their alignment. Of these two strategies the V groove provides the most effective alignment because the line of contact on the baseplate lies on a planar surface (as opposed to a sharp corner in the case of the rectangular slot). Indeed, the drawback to rectangular-slot baseplates is their poor alignment repeatability owing to the degradation of the edge's sharpness after repeated insertions. On the other hand, the drawback to V grooves is an increase in machining costs. The baseplate approach that is proposed here combines both of these advantages: alignment repeatability and ease of machining. Furthermore, a derivative and significant advantage for using rods as an alignment reference is that they can be used to align the OPS module kinematically to the interconnect baseplate because they define the optomechanical axis of the OPS module. The mounting technique of the OPS baseplate to the interconnect baseplate is described in Section 7.

A schematic diagram of the optomechanics is shown in Fig. 6, and the different optomechanical components are described in the following subsections. In the discussion, lateral alignment refers to the direction perpendicular to the OPS module

optical axis (x-y), whereas longitudinal alignment refers to the direction of light propagation, that is parallel to the OPS module optical axis (z).

A. Optical-Power-Supply Baseplate

The support for the cells of the OPS module consists of a slot baseplate 150 mm (long) $\times$ 40 mm (wide) $\times$ 15 mm (high) with the extremities being 25 mm high. For ease of machining and reducing weight the OPS baseplate are machined out of aluminum. The baseplate is also compatible with ϕ 25-mm commercial optomechanical components so that the OPS modules can easily be assembled and characterized separately.

For accurately defining the distance between the rods and ensuring their parallelism two alignment holders are used to position and align the rods on the OPS baseplate. Each holder consists of a rectangular piece through which two holes providing a tight sliding-fit clearance for the rods have been machined. The holes on the holders are machined such that their position is within 5 μ m of the design value. Because the rods are aligned with the help of holders, the machining tolerances of the OPS baseplate, such as the position and the width of the slot, can be relaxed. Only one pair of holders is necessary to align the rods on all four OPS baseplates.

B. Cell Holders

All cells are machined out of 416 stainless steel such that they can be held in place by the magnets in the OPS baseplate during their alignment. The lateral alignment of the QWP, the RPP's, and the FOG is not critical. Thus the components are positioned manually and glued to 25-mm cells. On the other hand, the fiber, collimating lenses, Fourier lens, and

lenslet array must be aligned accurately to a common optical axis. To do so requires that the components be centered within cells machined to an outer diameter of 25.00 ± 0.01 mm. The lenslet-array alignment technique utilizes lithographically defined metal markers that are deposited on the substrate during the lenslet-etching process. The lenslet array is centered relative to its cell by the alignment of the markers present on the substrate to those machined on the cell. It is then fixed by use of UV-cured epoxy; its alignment precision to the optomechanical axis of the cell was measured to be within 30 μ m.

C. Collimation Barrel

It was decided to mount the fiber and the collimating lenses in a single barrel, referred to as the collimation barrel (see Fig. 7). This approach allows the collimating module to be easily inserted and removed from the OPS module, while maintaining alignment and collimation accuracy. The aspheric and the achromatic lenses are first mounted in Delrin cells by use of an interference fit between the cell and the lens-edge surface [29]. This type of fitting automatically centers the lenses to the mechanical axes of their cells. The outer diameters of the Delrin cells are machined to provide a close sliding-fit clearance to the inner diameter of the collimation barrel so that they can easily be inserted and removed from the barrel, while ensuring their alignment with its optomechanical axis.

The interior of the collimation barrel is divided into two sections by a stopper: The fiber receptacle is placed on one side, whereas the collimating lenses are inserted on the other side. The longitudinal positions of the lenses are adjusted by a combination of spacers inserted between both the stopper and the first collimating lens and between the two

lenses. The spacers and the lenses are held in place with a retainer ring that is fixed by use of four screws. Finally, the design of the collimation barrel includes a groove to allow easy access to the cells inside the barrel.

The mechanism for centering the fiber with the optomechanical axis of the collimation barrel is shown in Fig. 8. The end plate of a fiber-connect-physical-contact fiber receptacle is chamfered down at 45°, as shown. The fiber receptacle is placed in contact with the stopper of the collimation barrel and four cup-point-locking screws (to minimize backlash and provide stable positioning) are driven against the chamfered edge to hold the receptacle in place. The screws are then used to adjust the lateral position of the fiber receptacle. Using this mechanism allows the fiber to be centered to the optomechanical axis of the collimation barrel with a precision of better than 6 μm . Furthermore, after numerous removals from and insertions into the receptacle of the fiber, the deviation of the fiber from its initial position is within 1 μm . This mechanism is an improved version of that presented in Ref. 20 in which the receptacle was chamfered down in a circular fashion and permitted an alignment precision of 10 μm .

6. Assembly and Alignment

The first step in the assembly of the OPS module is the assembly of the collimation barrel. After the receptacle has been centered the design requires that the positions of the collimating lenses be adjusted to produce a collimated beam with waist radius between 610 μm $< \alpha_{\text{w}} < 640 \mu\text{m}$ in both x and y . However, it was found that the size of the beam waists needed to be slightly larger than the theoretical value, that is, between 640 μm $<$

$\alpha_{\text{w}} < 670 \mu\text{m}$, to produce the required spot size (13.1 μm) at the modulators. This need can be explained by the tolerance on the focal length of different components in the OPS module and the optical interconnect and by possible variation of the mode-field diameters for different fibers.

It was noted that the beam at the output of the collimation barrel had a small angular deviation with respect to the optomechanical axis of the barrel. This deviation can be attributed to the sliding-fit clearance required for the insertion of the cells into the collimation barrel, resulting in the lenses being not perfectly centered on the optical axis. However, this angular deviation can be reduced to less than 0.01° by a slight adjustment of the position of the fiber receptacle to compensate for this misalignment.

The second step of the assembly consists of adjusting the focal length of the Fourier lens to produce a spot array with the required pitch. To do so requires that an alignment mask replicating the ideal spot position be designed and mounted on a cell by use of the same technique as for the lenslet array (Subsection 5.B). Positioning the collimation barrel, the FOG, the Fourier lens, and the alignment mask on the OPS baseplate allows the spot array to be observed on the alignment mask. The focal length of the Fourier lens is then adjusted to align the spot array onto the markers, ensuring that the required pitch is obtained.

After all the collimation barrels and Fourier lenses have been adjusted it is possible to align an OPS module in less than 15 min, as follows. When the cells are deposited onto the rods in the baseplate four out of six mechanical degrees of freedom are constrained: (Only the roll and the longitudinal position of the elements need to be adjusted. Given

that a collimated beam is output from the collimation barrel, the longitudinal alignment of only three elements is critical:

- i) The FOG must be positioned at the front focal point of the Fourier lens.
- ii) The distance between the Fourier lens and the OPS lenslet array (LA_1) must be equal to the back focal length of the Fourier lens plus f_{LA} such that the output beams of the OPS module are collimated.
- iii) The OPS lenslet array LA_1 must be positioned at a distance of $f_{LA} \pm 500 \mu m$ from the PMG after the OPS baseplate is inserted into the interconnect baseplate (to preserve the interconnect system telecentricity).

Furthermore, the roll of only three elements needs to be adjusted:

- i) The roll of the FOG must be adjusted so that the spot array at the output of the OPS module is rotationally aligned with the PMG and the interconnect system.
- ii) The roll of lenslet array LA_1 must be adjusted so that it is rotationally aligned with the spot array at the output of the Fourier lens.
- iii) The roll of the QWP must be adjusted to circularize the light polarization to maximize power transfer to the interconnect system.

The first step in the alignment of an OPS module is to position the Fourier lens by hand to within $200 \mu m$ of its ideal position. Next, the position of the FOG is adjusted by the imaging of the grating through the Fourier lens onto a screen placed approximately 50 cm from the Fourier lens. Only when the FOG is at the front focal point of the Fourier lens will a clear image of the grating be visible on the screen. Using this technique allows the position of the FOG to be estimated to be aligned to within $50 \mu m$ of the Fourier lens's

front focal point. The rotational alignment of the FOG is then performed by rotation of the cell by hand such that the beams at its output are parallel to markers on an alignment mask.

Next, lenslet array LA_1 is deposited onto the baseplate and rotated such that its columns of minilenses are parallel to the incident beams. Because of the imperfect alignment of the LA_1 with respect to the mechanical center of its cell the RPP is then rotated such that each spot of the array is aligned in the center of a minilens. The longitudinal position of LA_1 is then adjusted to collimate the beam by minimization of the divergence angle of the spot array.

Finally, the assembly of the OPS module is completed by the insertion of the QWP into the baseplate and the adjustment of its roll such that the power transmission into the interconnect is maximized. This step is performed after the OPS baseplate has been mounted on the interconnect baseplate. A photograph of an assembled OPS module is shown in Fig. 9.

7. Insertion of the Optical-Power-Supply Baseplate into the Interconnect Baseplate

The most critical part of the optomechanical design for the OPS module is its attachment to the interconnect baseplate. To better understand the attachment technique and the packaging of the second stage of the array generator system, we first present a short overview of the interconnect baseplate. The mounting technique is then described in

Subsection 7.A, and the characterization of the repeatability of the insertion is presented in Subsection 7.B.

A. Overview of the Interconnect Baseplate

The interconnect baseplate is designed as the optomechanical reference to which all modules are aligned (see Fig. 2). For simplicity and ease of assembly the modules are passively aligned by use of rods, holes, and dowel pins. The beam-combination and the beam-relay modules are packaged in the slot of the interconnect baseplate, whereas the OPS and chip modules are mounted on the baseplate. The technique for the alignment of the PMG (which is part of the beam-combination module) on the interconnect baseplate is shown in Fig. 10. The PMG substrate is precisely diced, and its edges are placed against three dowel pins. A clamp is then used to hold the module in place. The lenslet array in the second stage of the array generator (LA_2) is packaged in the chip module. This chip module is mounted on the interconnect baseplate by the mating of the chip-module holder to two precision-ground dowel pins. This technique is described further in Ref. 22.

B. Optical-Power-Supply Baseplate Mounting Technique

Each OPS module must be inserted at 90° to the plane that contains the optical axis of the ring interconnect. The attachment of the OPS module to the optical interconnect is achieved by the mating of the rods of the OPS baseplate to holes machined in the interconnect baseplate. The holes have the same specifications as that of the rod-alignment holder (see Subsection 5.A). They are designed to provide a tight sliding-fit

clearance for the rods and machined to within $5\text{ }\mu\text{m}$ of the design value. The measured rod diameter is $4.990 \pm 2\text{ }\mu\text{m}$, whereas the specification for the diameter of the holes is $5.004 +0.012/-0.000\text{ }\mu\text{m}$.

The rods together with the flat surfaces of the baseplates provide a kinematic reference that constrains angular movement (both rotation and tilt). Furthermore, because the optical axis of the OPS module is defined by the two rods, any inaccuracy in the position of the OPS's optical axis is limited to the relative positioning error of the holes in the interconnect baseplate to the other features on the interconnect baseplate. Finally, the OPS baseplate is fixed in place with screws in oversized holes. The mounting of the OPS baseplate to the interconnect baseplate is shown in Fig. 10.

C. Kinematic-Alignment-Mechanism Characterization

To validate the design approach for the mounting of the OPS module, we fabricated a prototypical baseplate. A substrate that replicated the ideal spot array was aligned on the baseplate in place of the PMG and by use of the same technique. The OPS baseplate was removed, reinserted, and secured in place 30 times. For every extraction-insertion cycle, the lateral and the angular misalignments of the beam array with respect to the alignment substrate were noted, and the results are shown in Fig. 11. The average lateral misalignment is $154\text{ }\mu\text{m}$ in x and $123\text{ }\mu\text{m}$ in y , whereas the angular misalignment is 0.171° in x and 0.036° in y . The position and the angle of incidence of the beams on the substrate can be adjusted by use of the RRP such that the small misalignments can be eliminated.

The repeatability of the insertion can be characterized by a comparison of the misalignment standard deviations with the alignment tolerance between the OPS module and the optical interconnect for a 1% power loss. These tolerances, which were presented in Table 1, are $5.5 \text{ } \mu\text{m}$ (lateral) and 0.05° (angular). The standard deviation for the lateral misalignment is $\sigma_x = 5.8 \text{ } \mu\text{m}$ and $\sigma_y = 4.1 \text{ } \mu\text{m}$, whereas it is $\sigma_\alpha = 0.004^\circ$ and $\sigma_\beta = 0.006^\circ$ for the angular misalignment. The results indicate that, after the RRP has been adjusted to align the beams onto the modulators, the OPS baseplate can be removed and passively reinserted such that all the beams remain aligned on the chip.

8. Characterization

Four OPS modules were implemented, and a detailed characterization of the performance was carried out. The goal was to obtain statistical information on the reproducibility of the design and implementation. The results are presented in the following subsections.

A. Spots and the Spot Array

There are three main parameters that must be characterized for the spot array: the spot size, the array pitch, and the array power uniformity. The measured values of these parameters for all four OPS modules are shown in Table 3, and a photograph of the spot array at the modulators is shown in Fig. 12. Because the system is telecentric, the spot size at the modulators is the same as that at the output of the Fourier lens. For this reason a beam profiler mounted on a micrometer stage was used to measure the spot size at the back focal point of the Fourier lens. The average value is $13.2 \text{ } \mu\text{m}$, whereas the worst-case measurement ($13.7 \text{ } \mu\text{m}$) is within $0.6 \text{ } \mu\text{m}$ of the design value.

The pitch of the 4×8 array was measured by means of placing a mask at the back focal point of the Fourier lens. The positions of the four outer spots were monitored on the mask, as shown in Fig. 13. The pitch of the array was derived by measurement of the spot displacements from the markers and then distribution of the error over the entire array. This technique allows the evaluation of the worst-case spot pitch because displacements of the outer spots are largest as a result of distortion and aberrations. This also explains the fact that the steeper pitch ($1600 \text{ } \mu\text{m}$) is not exactly twice as large as the lesser one ($800 \text{ } \mu\text{m}$). The worst pitch, which is $1602.2 \pm 0.4 \text{ } \mu\text{m} \times 801.5 \pm 0.2 \text{ } \mu\text{m}$ (OPS module 3), is within the tolerance of the system. A similar technique was utilized to characterize the spot pitch of the 4×4 array. An OPS module was inserted into the interconnect baseplate, and the pitch of the outermost cluster was measured. The result was $89.1 \pm 0.2 \text{ } \mu\text{m} \times 89.1 \pm 0.2 \text{ } \mu\text{m}$, which is excellent.

A common metric for quantifying the uniformity of FOGs is to consider that the power distribution in the array approximates a normal distribution and to calculate the standard deviation. Using this metric showed the measured nonuniformity for the 4×8 array produced by the FOGs to be 12%. However, because the system employs differential encoding and because pairs of beams illuminating the modulators and the detectors are created at the PMG, these beams will have the same relative offset. Thus the uniformity of the PMG is more critical than that of the FOG. For the 4×4 array generator in the PMG, the average nonuniformity is 4%, and no significant zero-order beam is present in any of the spot arrays. Thus pairs of beams in a data channel will have almost identical power at the modulators.

B. Power Budget and Efficiency

Throughput efficiency measurements were performed on each of the optical elements of the array-generation system, and the averages are listed in Table 4. The values for the diffractive optical elements (FOG, PMG, and lenslet array) include both diffraction and reflection losses. The throughput of all components was within specifications except for the FOG and the PMG. The low efficiency and high nonuniformity of the FOG are most probably attributable to the difficulty of designing an element that produces such a large diffraction angle. The low efficiency of the PMG is probably attributable to fabrication errors. Given the low efficiency of these two components, the cumulative throughput for the array-generation system was measured to be $33\% \pm 5\%$.

9. Conclusion

A robust, compact, and modular OPS spot-array generator has been implemented successfully to drive an array of 512 modulators used in a free-space optical interconnect. The design requirements presented in Table 1 were met successfully. The optomechanical design for the OPS module allows that the module be aligned kinematically to the interconnect system by use of precision-ground rods and tight sliding-fit holes as a reference. This kinematic alignment results in a module that is both easy to assemble and easy to use. Furthermore, the alignment of the OPS module to the interconnect system is repeatable such that it can be unmounted and remounted without requiring any realignment. Note that light was routed successfully from the modulators to the detectors in the optical interconnect [21], thus further demonstrating that the requirements for the OPS were satisfied.

10. Acknowledgment

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11. References

- [1] F.A.P. Tooley, "Challenges in optically interconnecting electronics," *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 2, No. 1, p. 3-13, April 1996.
- [2] O. Kibar, D. A. Van Blerkom, C. Fan and S. C. Esener, "Power minimization and technology comparisons for digital free-space optoelectronic interconnections," *Journal of Lightwave Technology*, Vol. 17, No. 4, p. 546-555, April 1999.
- [3] C. Fan, D. A. Van Blerkom, W. L. Hendrick, and S. C. Esener, "Free-space optical interconnection: a technology comparison of vertical-cavity surface-emitting lasers and multiple-quantum-well modulators," *Optical Review (Japan)*, Vol. 3, No. 6A, p. 394-396, 1996.
- [4] A. L. Lentine, "Qualitative comparison of MQW modulator and VCSEL based OE-VLSI: a systems perspective," *IEEE LEOS*, Vol. 2, p. 83-84, 1996.
- [5] L. A. Coldren, E. Hegblom, E. Strzelecka, J. Ko, Y. Akulova, and B. Thibault, "Recent advances and important issues in vertical-cavity lasers," *Proceedings of the SPIE*, Vol. 3003, p. 2-13, 1997.
- [6] R. A. Morgan, "Vertical-cavity surface-emitting lasers: present and future," *Proceedings of the SPIE*, Vol. 3003, p. 14-26, 1997.
- [7] A. V. Krishnamoorthy, L. M. F. Chirovsky, W. S. Hobson, R. E. Leibengath, S. P. Hui, G. J. Zyzik, K. W. Gossen, J. D. Wynn, B. J. Tseng, J. Lopata, J. A. Walker, J. E. Cunningham, and L. A. D'Asaro, "Vertical-cavity surface-emitting lasers flip-chip bonded to gigabit-per-second CMOS circuits," *IEEE Photonics Technology Letters*, Vol. 11, No. 1, p. 128-130, Jan 1999.
- [8] A. V. Krishnamoorthy and K. W. Gossen, "Progress in optoelectronic-VLSI smart pixel technology based on GaAs/AlGaAs MQW modulators," *International Journal of Optoelectronics*, Vol. 11, No. 3, p. 181-198, 1997.
- [9] D. V. Plant, A. Z. Shang, M. R. Otazo, D. R. Rolston, B. Robertson, and H. S. Hinton, "Design, modeling, and characterization of FET-SEED smart pixel transceiver arrays for optical backplanes," *IEEE Journal of Quantum Electronics*, Vol. 32, No. 8, p. 1391-1398, Aug. 1996.
- [10] H. S. Hinton, T. J. Cloonan, F. B. McCormick, A. L. Lentine, and F. A. P. Tooley, "Free-space digital optical systems," *Proceedings of the IEEE*, Vol. 82, No. 11, p. 1632-1649, 1994.
- [11] D. T. Neilson, S. M. Prince, D. A. Baillie, and F. A. P. Tooley, "Optical design of a 1024-channel free-space sorting demonstrator," *Applied Optics*, Vol. 36, No. 35, p. 9243-9252, December 1997.
- [12] B. Robertson, "Design of an optical interconnect for photonic backplane applications," *Applied Optics*, Vol. 37, No. 14, p. 2974-2984, May 1998.
- [13] D. R. Rolston, B. Robertson, H. S. Hinton, and D. V. Plant, "Analysis of a microchannel interconnect based on the clustering of smart-pixel-device windows," *Applied Optics*, Vol. 35, No. 8, p. 1220-1233, March 1996.
- [14] N. Streibl, "Beam shaping with optical array generators," *Journal of Modern Optics*, Vol. 36, No. 12, p. 1559-1573, 1989.
- [15] H. Dammann and K. Gortler, "High-efficiency in-line multiple imaging by means of multiple phase holograms," *Optical Communications*, Vol. 3, No. 5, p. 312-315, 1971.
- [16] F. B. McCormick, "Generation of large spot arrays from a single laser beam by multiple imaging with binary phase gratings," *Optical Engineering*, Vol. 28, No. 4, p. 299-304, 1989.
- [17] J. Jahns, M. M. Down, M. E. Prise, N. Streibl, and S. J. Walker, "Dammann gratings for laser beam shaping," *Optical Engineering*, Vol. 28, No. 12, p. 1267-1275, 1989.

- [18] J. M. Miller, M. R. Taghizadeh, J. Turunen and N. Ross, "Multilevel-grating array generators: fabrication error analysis and experiments," *Applied Optics*, Vol. 32, No. 14, p. 2519-2525, 1993.
- [19] N. C. Craft and M. E. Prise, "Optical system tolerances for symmetric self electro-optic effect devices in optical computers," *Topical Meetings on Optical Computing, Optical Computing 1989 Technical Digest Series, Volume 9, Salt Lake City, UT, USA*, p. 334-337, 1989.
- [20] R. Iyer, Y. S. Liu, G. C. Boisset, D. J. Goodwill, M. H. Ayliffe, B. Robertson, W. M. Robertson, D. Kabal, F. Lacroix, and D. V. Plant, "Design, implementation, and characterization of an optical power supply spot-array generator for a four-stage free-space optical backplane," *Applied Optics*, Vol. 36, No. 35, p. 9230-9242, December 1997.
- [21] F. Lacroix, B. Robertson, M. H. Ayliffe, E. Bernier, F. A. P. Tooley, M. Châteauneuf, D. V. Plant, and A. G. Kirk, "Design and implementation of a four-stage clustered free-space optical interconnect," *Proceedings of the SPIE*, Vol. 3490, p. 107-110, 1998.
- [22] M. H. Ayliffe, D. Kabal, P. Khurana, F. Lacroix, A. G. Kirk, F. A. P. Tooley, and D. V. Plant, "Electrical, thermal and optomechanical packaging of large 2D optoelectronic device arrays for free-space optical interconnects," *J. Opt. A: Pure Appl. Opt.*, Vol. 1, No. 2, p. 267-271, March 1999.
- [23] B. Robertson, Y. Liu, G. C. Boisset, M. R. Taghizadeh, and D. V. Plant, "In situ interferometric alignment systems for the assembly of microchannel relay systems," *Applied Optics*, Vol. 36, No. 35, p. 9253-9260, 1997.
- [24] A. G. Kirk and T. J. Hall, "Design of computer generated holograms by simulated annealing: coding density and reconstruction error," *Optical Communication*, Vol. 94, No. 6, p. 491-496, 1992.
- [25] B. E. A. Saleh, M. C. Teich, *Fundamentals of Photonics*, Wiley & Sons Inc, New York, Chapter 3, 1991.

- [26] Warren J. Smith, *Modern Optical Engineering*, Second Edition, McGraw-Hill Inc., Chapter 11, 1990.
- [27] J. L. Brubaker, F. B. McCormick, F. A. P. Tooley, J. M. Sasian, T. J. Cloonan, A. L. Lentine, S. J. Hinterlong, and M. J. Herron, "Optomechanics of a free space photonic switch: the components," *Proceedings of the SPIE*, Vol. 1533, p. 88-96, 1991.
- [28] F. B. McCormick, F. A. P. Tooley, J. L. Brubaker, J. M. Sasian, T. J. Cloonan, A. L. Lentine, R. L. Morrison, R. J. Crisci, S. L. Walker, S. J. Hinterlong, and M. J. Herron, "Optomechanics of a free space photonic switch: the system," *Proceedings of the SPIE*, Vol. 1533, p. 97-114, 1991.
- [29] G. C. Boisset, M. H. Ayliffe, B. Robertson, R. Iyer, Y. S. Liu, D. V. Plant, D. J. Goodwill, D. Kabal, and D. Pavlasek, "Optomechanics of a four-stage hybrid-self-electro-optic-device-based free-space optical backplane," *Applied Optics*, Vol. 36, No. 29, p. 7341-7358, Oct. 1997.

12. Tables

Table 1 – Optical-Power-Supply Requirements

Optical requirements	Requirement	Measured
Wavelength	852.0 nm	852.0 ± 0.1 nm
4 × 8 array of cluster pitch	1600 × 800 μm	1602.2 ± 0.4 μm × 801.5 ± 0.2 μm *
4 × 4 cluster array pitch	90 × 90 μm	89.1 ± 0.2 μm × 89.1 ± 0.2 μm
Beam waist at modulators (1/e ²)	13.1 μm	ω _x = 13.7 ± 0.1 μm * ω _y = 13.4 ± 0.1 μm *
Input polarization linearity	100:1	1500:1
Optomechanical Requirements for a 1% power loss for the OPS module	Requirement	Measured
Roll around the optical axis	45 arc minutes (0.75°)	< 6 arc minutes (0.1°)
Lateral alignment repeatability	55 μm	σ _x = 5.8 μm σ _y = 4.1 μm
Angular alignment repeatability	3 arc minutes (0.05°)	σ _x = 0.004° σ _y = 0.006°

* Worst case out of four implementations

Table 2 – OPS module degrees of freedom

Design Requirement	Optical / Optomechanical Solution
Spots on a uniform grid	Low distortion Fourier lens
Spot pitch of 1600 × 800 μm	Adjust focal length of Fourier lens by changing element separation
Spot size of 13.1 μm (1/e ²)	Adjust focal length of collimating lens by changing element separation
Collimated beam through the FOG	Maintain the fiber facet at the front focus of the collimating lens
Angular alignment of the collimated beam	Adjust the fiber receptacle lateral position on the collimation barrel
Angular alignment of spot array about the optical axis	Rotate the FOG about the optical axis
Mutual angular alignment of chief rays of all beams in the spot array	Position the FOG at the front focus of the Fourier lens; Low aberration Fourier lens
Lateral alignment of the spot array	Rotate the RPP about the optical axis

Table 3 – Characterization results for the four OPS modules

	OPS 1	OPS 2	OPS 3	OPS 4
Spot pitch (μm)	1601.2 ± 0.4 $\times 801.2 \pm 0.2$	1602.0 ± 0.4 $\times 800.7 \pm 0.2$	1602.2 ± 0.4 $\times 801.5 \pm 0.2$	1602.4 ± 0.4 $\times 799.7 \pm 0.2$
Fourier lens spot size (μm)	$\omega_x = 13.4 \pm 0.1$ $\omega_y = 13.1 \pm 0.1$	$\omega_x = 13.0 \pm 0.1$ $\omega_y = 12.9 \pm 0.1$	$\omega_x = 13.0 \pm 0.1$ $\omega_y = 12.9 \pm 0.1$	$\omega_x = 13.7 \pm 0.1$ $\omega_y = 13.4 \pm 0.1$
Fan-out grating nonuniformity	$12 \pm 1\%$	$11 \pm 1\%$	$11 \pm 1\%$	$11 \pm 1\%$
Patterned mirror nonuniformity	$3 \pm 1\%$	$4 \pm 1\%$	$4 \pm 1\%$	$4 \pm 1\%$

Table 4 – Throughput efficiency of the array-generation system

Optical Component	Measured value
Collimation barrel	$99 \pm 1\%$
Risley prism pair	$99 \pm 1\%$
Quarter-wave plate	$99 \pm 1\%$
Fan-out grating (diffraction efficiency and reflection loss)	$70 \pm 2\%$
Fourier lens	$95 \pm 1\%$
Minilens (diffraction efficiency and reflection loss)	$84 \pm 2\%$
Patterned-mirror grating (diffraction efficiency and reflection loss)	$72 \pm 2\%$
Minilens (diffraction efficiency and reflection loss)	$84 \pm 2\%$
Total efficiency	$33 \pm 5\%$

Figures Captions

Figure 1 – Schematic diagram of the externally generated spot array

Figure 2 – Schematic diagram of the ring-based optical backplane

Figure 3 – Schematic diagram of the optical interconnect design; LA: lenslet array; Note that the array size of the OI-VLSI chip and lenslet array is 8×8 (and not 4×4), and that the PMG array size is 8×1 (and not 4×1 as shown)

Figure 4 – Schematic diagram of the array-generation system (in μm)

Figure 5 – Schematic diagram of the optical design for the OPS; PM: polarization-maintaining; CL: collimating lens; QWP: quarter-wave plate; RPP: Risley prism pair; LA: lenslet array

Figure 6 – Schematic diagram of the OPS module optomechanics

Figure 8 – Schematic diagram of the collimation barrel

Figure 9 – Schematic diagram of the fiber centering mechanism

Figure 10 – Photograph of an assembled OPS module

Figure 12 – Schematic diagram of the OPS module insertion in the interconnect baseplate

Figure 13 – Characterization of the OPS baseplate insertion repeatability; (a) Lateral repeatability (μm); (b) Angular repeatability ($^\circ$)

Figure 14 – Photograph of the 512-spot array

Figure 15 – Photograph of the 4×8 spot array on the mask substrate

Figures

Figure 1 – Schematic diagram of the externally generated spot array

Figure 2 - Schematic diagram of the ring-based optical backplane

Figure 3 - Schematic diagram of the optical interconnect design
LA: lenslet array; Note that the array size of the OE-VLSI chip and lenslet array is 8×8 (and not 4×4 as shown), and that the PMIG array size is 8×1 (and not 4×1 as shown)

Figure 4 - Schematic diagram of the array-generation system (in μm)

Figure 5 - Schematic diagram of the optical design for the OPS
 PM: polarization maintaining; CL: collimating lens; QWP: quarter-wave plate;
 RPP: Risley prism pair; LA: lenslet array

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Figure 12 – Schematic diagram of the OPS module insertion in the interconnect baseplate

Figure 13 – Characterization of the OPS baseplate insertion repeatability
(a) Lateral repeatability (μm); (b) Angular repeatability (°)

Figure 14 – Photograph of the S12-spot array

Figure 15 – Photograph of the 4 x 8 spot array on the mask substrate