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Modular Photonic Power and VCSEL-Based Data Links for Aerospace and Military Applications

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Abstract— If photonic data and power transfer links are constructed in a modular fashion, they can be easily adapted into various forms to meet a wide range of needs for aerospace and military applications. The performance specifications associated with these needs can vary widely according to application. Alignment tolerance needs also tend to vary greatly, as can requirements on power consumption. An example of a modular photonic data and/or power transfer link that can be applied to military and aerospace needs is presented. In this approach, a link is designed for low (<10 kb/s) data rates, ultra-low electrical power consumption, large alignment tolerance, and power transfer to provide complete electrical shielding in a remote module that might be found in a military or aerospace application.

TABLE OF CONTENTS

1. INTRODUCTION
2. DESIGN CRITERIA FOR THE ISOLATING PHOTONIC POWER AND DATA LINK
3. DEVICE TECHNOLOGIES AND OPTICAL DESIGNS FOR PHOTONIC POWER AND DATA TRANSFER
4. PACKAGE REALIZATION
5. INTERFACE CIRCUITRY
6. SUMMARY AND CONCLUSIONS

1. INTRODUCTION

Modular photonic data and power transfer links can perform a number of functions that address the unique requirements of aerospace and military applications. This implies performance levels and design specifications that can vary (according to application) from single channels carrying data rates of a few kb/s to multiple channels needing data throughputs in the 10s to 100s of Gb/s.

Alignment accuracy, data rate, and power consumption limitations form a three-dimensional design space for modular photonic data links. In general, higher data rates imply tighter alignment tolerance and larger levels of power consumption. This design space is explored for an ultra low power consumption, a high alignment tolerance, and a relatively low data rate as described below.

In some of the applications associated with the military and aerospace environment, the primary motivation for the use of photonics is to provide very high levels of isolation between modules, thus effecting great immunity to electromagnetic and radio frequency interference (EMI and RFI). In cases where the photonic channels are not required to transmit analog radio frequency data, this may

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Figure 1 Two versions of the modular optoelectronic isolating power and data interconnect.

imply low data rate and (in cases where an extremely high EMI immunity is required) may even involve the use of photovoltaic (PV) cells to provide power to remote modules. In such applications, low power consumption for the data link in the remote module may be especially important, since a high power conversion penalty is associated with the use of remote PV power. The additional need for a large alignment tolerance and a packaging form factor that mimics present electrical connector technology leads to a modular approach using external spherical lenses for collimation and re-focus in the photonic interconnection channels. Here, Vertical Cavity Surface-Emitting Lasers (VCSELs) are used for their advantages of low power consumption and low-divergence circular output beams.

2. DESIGN CRITERIA FOR THE ISOLATING PHOTONIC POWER AND DATA LINK

Many aerospace applications require isolation of remote modules from Electromagnetic Interference (EMI) and Radio-Frequency Interference (RFI). While this has specific application to military and avionics systems that must often be placed near radars, an EMI-

resistant link may also enable new applications such as fly-by-light systems for aircraft.

Baseline Design

The isolating optical link is a modular design in which the optical beams are expanded, collimated, and passed through a non-conductive interface. The interconnect can then be housed in an electrical connector body and used as a high-isolation connector for input and output of signals and input of power into a remote, electrically-isolated region as in Figure 1a. Alternatively, the signals can be focused into optical fibers as in Figure 1b for transmission between Faraday cages through particularly noisy regions of use, thus assuring data fidelity, noise immunity, and Faraday cage integrity as in Figure 1b.

The baseline design for the isolating optoelectronic connector mimics an electrical connector body for ease of handling, assembly and compatibility with present electrical connector components. The prototype unit is approximately the size of an electrical 25 pin "D" connector. It carries multiple power and bi-directional data channels and is to be compatible with low power 3V electronic systems. The connector uses use Vertical

Figure 2 Schematic of bulkhead connector details.

Cavity Surface-Emitting Lasers (VCSELs) and detectors for data links as in Figure 2, that will be optimized for lowest power consumption. The design also makes use of high-power fiber-coupled lasers, which illuminate multiple center-tapped six-junction photovoltaic (PV) arrays for power transfer to the remote, electrically-isolated modules of Figure 1. The bulkhead version of the module appears in greater detail as in Figure 2, where the power and data is passed through an EMI barrier as shown. VCSELs, detectors, and optical fibers are all held in alignment by submounts within the connector body, and the light beams pass between the two sides of the connector through windows that contain collimating optics. As an alternative, separate collimating optical elements could be included behind the windows. Such a design could enable hermeticity and increase immunity to dirt between the connectors.

The Modular Approach

By designing for maximum modularity, the same device, submount, and optics

arrangements from the bulkhead connector of Figure 1a could be used directly with an optical fiber to provide data and power as in Figure 1b. This criterion further constrains the design of the submount and optics, and implies maximum use of the collimation and re-focusing approach to light transfer. The modular concept is described by the cross-section of Figure 3, where a single connector pair using the same submounts and optics can either be connected directly or via optical fibers.

Figure 3 clearly shows the utility of the collimation and re-focus lenses in the modular connector design. Such approaches have previously used coupling spheres to maximize the tolerance between optical fibers in lens-based couplers [1]. Here, the entire optical submount assembly can be realized, complete with VCSELs, detectors, lenses, and ceramic submounts. Optical fibers can be substituted directly for devices in the realization of Figure 3b. When all light entering or leaving the optical submount assembly is collimated, the alignment tolerance between assemblies (and

a. Modular design for the bulkhead connector.

b. Modular bulkhead connector design applied to optical fiber connections.

Figure 3 Cross-section of the connector design showing how it can be applied both to a bulkhead version and to an optical fiber link.

thus between the connector bodies) is maximized. The only critical alignments then occur between the spherical lenses and their respective VCSELs, lenses, and/or detectors. The needed alignment accuracy at this level can be realized by precision-drilled submounts and alignment pins as will be described.

3. DEVICE TECHNOLOGIES AND OPTICAL DESIGNS FOR PHOTONIC POWER AND DATA TRANSFER

Optimal realization of the connector design shown in Figures 2 and 3 is dependent on the availability of appropriate device technologies for the realization of the data and power transfer channels. In general, the source and detector devices to be used should exhibit high

efficiency, low voltage and low current operation. For the spherical lens-based designs of Figure 3, circular output beams and detector area symmetry are also highly desirable.

For ultimate application to the aerospace environment, the devices to be used in this connector should have a capability for operation over a wide temperature range and must exhibit high reliability. Though extended temperature and reliability data are presently beyond the scope of this work, the device technologies have been chosen to enable eventual high-reliability operation over wide temperature ranges.

Data Channel Devices and Designs

VCSELs—Surface emitting lasers are ideal for the type of isolating connector design described here. They can exhibit very high electrical-to-optical conversion efficiency [2], low voltage operation [3], can have nominally circular output beams that propagate with low divergence [4], and can be designed for operation over wide ranges of temperature [5].

For the design of Figure 2, two different VCSEL devices can be used to optimize for low power consumption at the remote module. On the power source side (the EMI insensitive module of Figure 1), a relatively large amount of electrical power availability can be assumed. This is due to the fact that a large amount of power will be required to drive the power transmission laser, as discussed later. The VCSELs will add very little to this overall power consumption. On the remote module side of the connection, however, power consumption must be kept to a minimum, since the only available power comes from the PV cells (which must power both the electronics in the module, and the interconnect). Remote module power consumption can best be minimized by use of a relatively high VCSEL power coming from the insensitive module. This will minimize the amount of amplification needed for the photodetector to produce an output that is compatible with the 3V digital circuits in the remote module, and will thus minimize power consumption at the remote photoreceiver. A relatively low output power can then be tolerated from the VCSEL transmitting data back from the remote module, since the insensitive side can be assumed to have more power available for signal amplification from the detector.

The above power distribution considerations call for a VCSEL at the transmission side of the connector that is relatively large in area, and can thus emit a large overall power at the expense of higher threshold current. This device may either be constructed by the use of ion implantation to define the active area [4], or it may use a large-area oxide-confined design [2],[3]. The optimum VCSEL design for the remote module will have a relatively small output area, and will be oxide-confined for minimum threshold and maximum efficiency.

The operating conditions and layout patterns for the two chosen VCSEL designs are described in Figure 4a for the transmission-side VCSELs and in Figure 4b for the remote

a. Voltage, current, and light output for the transmission-side VCSEL.

b. Voltage, current, and light output for the remote-module VCSEL.

Figure 4 VCSEL characteristics and layout patterns.

module VCSELs. Each of the two laser designs operates at a nominal 850 nm wavelength. Note that the peak output power for the transmission VCSELs is 15.3 mW at a 30 mA input, but that the threshold current is over 12 mA. This is due to the relatively large (25 μm , nominal) diameter of the laser active area [6]. The remote module VCSEL of Figure 4b, however, has a much smaller area (a 6 μm by 6 μm nominal square aperture) and thus a much smaller threshold current of only 2 mA [7]. The peak output power is much smaller, (4.0 mW at 11 mA) due to the smaller laser gain volume and thermal limitations associated with the smaller cooling area available to the active laser region. Above this drive current, the laser output “rolls over” due to self-heating.

Detectors— The detector chosen for data transmission in this application is a silicon p-i-n diode structure that can efficiently collect the light transmitted by the VCSEL, with a measured responsivity of approximately 0.5 A/W. Because of the relatively low data rates (<10 kb/s) associated with the basic application of interest, a large (1.5 mm diameter) detector area can be used. This maximizes alignment tolerance and thus makes for a more robust design. The detector layout pattern appears in

Response at 850 nm $\approx$ 0.5 A/W

Figure 5 Layout pattern of the large-area silicon p-i-n detector.

Figure 5. Though this device features an outer guard ring, it is not used in this application.

Power Transmission / Devices and Designs

As shown in Figure 2, the optoelectronic isolating connector provides three-Volt power to the remote module. This is achieved by the use of a cross-sectional design that is similar to that of Figure 3. The design is modified as in Figure 6, where the light source is a high

Figure 6 Cross-section of the optical power channel design.

Figure 7 Center-tapped six-element PV cell array.

power, fiber-coupled laser that is remotely mounted from the connector body. A comparison between Figures 3 and 6 will show that one of the spherical lenses is removed in the power channel. This allows full illumination of the active region of the series-connected PV cell, with only a slight dependence on the distance within the optical axis. The same submount assemblies are used, but are adapted to align the optical fibers to the collimating lenses. An optical fiber link could also be applied in a manner similar to the adaptation of the data channel in Figure 3b.

Series-Connected PV Cells— Series-connected PV cells were chosen for use to provide electrically-isolated power to the remote module. Such photovoltaic power devices can be used in a variety of series-connected arrangements to provide various voltage and current levels for remote power applications [8]. The devices chosen for use here are six-element series-connector cells [9]. As shown in Figure 7, each of the p-n diode cells in the array is arranged as a pie slice in an overall circular collection area of approximately 1.5 mm diameter. The p-side of one cell is connected to the n-side of the next cell to form the series. These devices may be center-tapped as in Figure 7 by the use of an extra bond to ground at the third cell in the series. This allows the six-element array to provide +3V and -3V power to the remote module.

Typical photovoltaic power characteristics appear in Figure 8 for three elements of the six element array of Figure 7. Here, the overall array is illuminated uniformly with various levels of laser light at a wavelength of 830 nm. Note that the maximum power at an overall illumination level of 105 mW yields 11.7 mW out (3.0 V at 3.9 mW), with maximum power

Figure 8 Typical power output characteristics for the center-tapped PV array.

transfer occurring at a load of 770 Ohms. This is slightly greater than the 10 mW per-channel power requirement that is targeted for our prototype connector. If uniform illumination over the entire PV array is assumed, (half of the overall power on each of the three sets of cells) then the power conversion efficiency of the array is 22 percent.

There are several important factors that must be considered when using PV cells for remote power applications. The load resistance must be kept near the value that yields maximum power transfer. This may call for load balancing circuits and a distribution of several power channels to the remote module. To address this need, multiple +3V and -3V power channels are incorporated into the module design. A second factor that must be considered is uniformity of illumination. The light impinging upon the PV array of Figure 7 must be distributed equally over all of the cells in order to provide maximum photocurrent and predictable operating conditions. The critical factor influencing this is mode filling in the fiber pigtail from the power laser in Figure 6. The fiber must be fully mode-filled to assure uniform illumination. This may require that the fiber pigtail have some extra length and be wrapped as shown.

Power Lasers—As indicated by Figures 6 and 7, the laser needed for power transfer to the series-connected PV cell must be an externally-

Figure 9 Characteristics of the pigtailed power laser.

mounted device that can output approximately 100 mW from a fiber pigtail. The laser chosen is a SDL model 2320-N2. This laser is pigtailed using a 50 μ m diameter core optical fiber with a numerical aperture of 0.12 [10]. The device is packaged for a high heat load and features a package size of 30 mm by 12.7 mm by 12.7 mm high. A typical output characteristic appears in Figure 9. Note that the laser's light output can be considerably more than the needed 100 mW level, and that the design features a correspondingly high (180 mA) threshold current. Alternate laser designs could be better optimized for lower electrical power consumption at the needed level of output optical power, but would not provide the range of power that is desired for experiments on this initial prototype.

Optical Design

The optical data and power channels described by the cross-sections of Figures 3 and 6 are designed to be extremely tolerant to misalignments between connector bodies. The collimating and re-focusing lenses have a very high (> 0.9) numerical aperture and can thus be large, relative to the size of the optical beam. This helps to assure that the light coming from the VCSELs can be collected onto the detectors. The fact that the re-focusing lens in Figure 3a collects light into a large-area detector (Figure 5) gives additional tolerance. As long as the VCSEL beam is collimated and centered enough to be completely collected by the re-focus lens, the light will reach the detector.

A well-characterized collimation and re-focus lens system operating over greatest possible distance is particularly important from the standpoint of the intended RF isolation of this system. The cross-section of Figure 3a shows an aperture between the spherical lenses. This aperture (1.7 mm diameter) forms a RF waveguide. Though the cut off frequency of this waveguide is greater than 135 GHz, the

longest possible length-to-diameter ratio should be maintained to minimize RF energy transfer across the two sides of the connector. Thus, the distance between the lenses is 17 mm for a ten-to-one length-to-diameter ratio.

As described for the data channels of Figure 3, the critical alignment conditions occur between the VCSELs and the collimating lenses, thus putting constraints on the design tolerance of the ceramic submounts that hold both the lasers and the lenses. In order to quantify these constraints, the system was modeled using a Gaussian beam and thin lens approximation. For the equivalent 1.1 mm lens focal length, the calculated beam diameter at 17 mm from the lens is only 106 μm . If the VCSEL-to-lens offset is 25 μm , then the beam center offset is less than 400 μm . Though this offset is approximately twice that expected for the submount methods to be used, the beam is still well within the 1.7 mm collection aperture.

Because the actual optimal focal point of the spherical lens is dependent on the divergence of the input optical beam and beam divergence can vary with design and operating point, experiments were carried out to determine optimal focal point and to verify that the beam would be contained within the aperture defined by this design. At the optimal focal point, the spot size at 17 mm from the VCSEL was 300 μm , and the offset magnification at the plane was 15x. Under these conditions, the 1.7 mm aperture would constrain the maximum misalignment between lens and laser to 40 μm , which is 2 to 4 times greater than the expected tolerance of the submounts. Thus, optical design for the data channels is robust.

For the power channels, the beam is to be partially collimated, as indicated by Figure 6. It should just fill the 1.5 mm active area of the PV array of Figure 7. In order to test the parameters for this condition of operation, the size of the optical spot from a power laser

pigtail was measured at 19 mm from the 2 mm spherical lens collimating lens, which is anti-reflection coated for 850 nm. The measurement was carried out at the 19 mm plane (rather than the 17 mm distance used for the VCSEL) to account for the additional spacing of the PV cell beyond the plane of the 2 mm lenses (which are separated by 17 mm) in Figure 6. Here, a collimated image of the optical end face was obtained when the fiber-to-lens separation was 160 μm . Under this condition, the beam diameter at the 19 mm plane was only 0.8 mm. Thus, the fiber-to-lens distance was increased to 460 μm in order to defocus the beam and provide a larger (approximately 1.7 mm) spot that would slightly overfill the area of the PV cell array. At this larger fiber-to-lens separation, the offset magnification was 5 X, so that an assumed fiber-to-lens lateral misalignment of 25 μm would move the spot by 125 μm . Under this condition, the PV array would still be illuminated with a relatively uniform beam

4. PACKAGE REALIZATION

Ceramic Submounts

The ceramic submount stacks of Figures 3 and 6 must provide the needed alignment between devices, fibers and lenses, as defined by the optical system analysis. These submounts use laser drilling for precision alignment. In particular, the laser drilling allows for lens capture and alignment and layer-to-layer alignment of the four submounts in the stacks of Figures 3 and 6. In addition, the submounts perform the function of fiber mounting and alignment in Figure 6.

The device -level submount is shown in Figure 10. It contains metal interconnections to electrically connect the active optoelectronic parts in the connector to external wires. As indicated, the small hole in the center of each

Figure 10 Ceramic submount with precision laser drilled holes for aligning and holding devices and optical fibers.

device mounting pad is designed to align and hold an optical fiber precisely. Each of these $150\ \mu\text{m}$ diameter holes can also act as a precise centering reference for mounting the VCSELs and other devices on their respective pads. Other precision holes are provided for the pins that provide level-to-level alignment as in Figures 3 and 6.

Using the $150\ \mu\text{m}$ diameter holes as alignment features, VCSELs are mounted as in Figure 11. Though the VCSEL devices are presently aligned to the holes manually, future versions of this submount could make use of passive

alignment techniques such as a solder-ball mounting [11], [12]. The symmetric device layout pattern allows the VCSELs and detectors in the power transmission and remote module submount stacks to communicate when facing each other across the connector interface. Detector and photovoltaic array chips require less precise placement and thus are mounted by centering on the $2\ \text{mm}$ metal pads as shown. Note that the remote module submount of Figure 11a contains the PV arrays at the center five locations, while on the power transmission side (Figure 11b), those locations are left open for mounting the fibers from the transmission

Figure 11 Populated device submounts.

**Power Generation: Center (Photovoltaic)
Lens Holes Not Populated**

**Power Transmission: All Lens Holes
Populated with 2 mm Ball Lenses**

Figure 12 Submounts to hold the 2 mm spherical lenses. Steel pins (shown) provide alignment to the device submounts.

lasers. As indicated in Figures 3 and 6, an additional unpopulated device submount identical to that of Figure 10 is placed behind the main device submounts of Figure 11 to assure that the fiber has accurate angular alignment.

The ceramic lens submounts that make up the final two layers in Figures 3 and 6 appear in Figure 12. Here, the holes are laser-drilled with a diameter of 1.9 mm in order to center and capture the 2 mm coupling spheres with a predictable 100 μm space between the outer surface of the lens and the ceramic plate. On the power transmission side of the connector, all lens locations are populated so that beams from the fibers and VCSELs can all be collimated, and signals can be re-focused on the detectors. For the remote module lens submounts, lenses are omitted from the sites in front of the PV cells so that the collimated beams from the power laser fiber pigtails can completely fill the cells, as in Figure 6.

The fiber mounting and device alignment reference holes of Figure 11 and the lenses in Figure 12 are precisely aligned (to about $\pm 12.5 \mu\text{m}$) with respect to the 1 mm alignment pin holes. Using precision steel pins, this allows the device submounts to be aligned to the lens submounts, thus completing the submount assemblies as in Figures 3 and 6.

Figure 13 Cross-sectional scale drawing and picture of the mated connector pair.

Figure 14 Interface circuitry to achieve data exchange with extremely low power consumption at the remote module.

Connector Bodies

The optical submount assemblies are attached to mating metal connector bodies that provide the needed RF isolation and basic alignment of the collimated beams. The mated connector pair (with ceramic submount stack) for the basic prototype appears in cross-sectional scale drawing of Figure 13. The submount stacks are attached to the connector bodies using #0-80 screws. The prototype connector bodies are machined in aluminum and are shown with their respective submount stacks in the inset of Figure 13.

5. INTERFACE CIRCUITRY

In order to operate with lowest possible electrical power consumed at the remote module, the high-efficiency VCSELs should be turned in a low duty cycle mode. At the slow data rates of interest, this is relatively easy to achieve, since the lasers can be operated much

faster than the required data pulse width. The interface and laser drive circuitry shown in the schematic diagram of Figure 14 will achieve laser operation with an overall average power consumption of a few tens of microwatts. This is done by driving the VCSELs in the remote module with a CMOS short-pulse multivibrator, and providing a latched photoreceiver circuit at the power transmission module. A clocked pulse resets the latched CMOS receiver at each clock cycle.

6. SUMMARY AND CONCLUSIONS

An optical interconnection design has been presented that provides EMI-resistant data exchange and power transfer for a remote module. Unlike many optical interconnects, it operates in a parameter space that is characterized by low power consumption, low data rates, and a relatively large misalignment tolerance. The design, which emulates an

electrical connector, contains a number of unique features such as 1) the use of VCSELs that are optimized, with respect to input power and resulting output for their specific conditions of operation, 2) high-power fiber-pigtailed lasers and series-connected photovoltaic cells to provide electrical power to the remote module, 3) the use of spherical collimating and re-focus lenses to connect the modules, while accommodating connector-to-connector misalignment, resistance to dirt, and a possible migration to an optical fiber-based interconnection, and 4) stacked laser-drilled ceramic submounts for precise device-to-lens alignments. Though the various elements in the laboratory prototype versions of this connector require considerable amounts of manual assembly, the concepts used can be applied to higher degrees of assembly automation and miniaturization in the future.

REFERENCES

- [1] A. Nicia, "Lens Coupling in Fiber-Optic Devices: Efficiency Limits," *Applied Optics*, vol. 20, no. 18, pp. 3136-3146, 1981.
- [2] K. L. Lear, K. D. Choquette, R. P. Schneider, S. P. Kilcoyne, and K. M. Geib, "Selectively Oxidized Vertical Cavity Surface Emitting Lasers with 50% Power Conversion Efficiency," *Electronics Letters*, vol. 31, no. 3, pp. 208-209, 1995.
- [3] K. D. Choquette, R. P. Schneider, Jr. K. L. Lear, and K. M. Geib, "Low Threshold Voltage Vertical-Cavity Lasers Fabricated by Selective Oxidation," *Electronics Letters*, vol. 30, no. 24, pp. 2043-2044, 1994.
- [4] L. A. Coldren and B. J. Thibeault, "Vertical-Cavity Surface-Emitting Lasers for Free-Space Interconnects" *SPIE Critical Reviews of Optical Science and Technology: Optoelectronic Interconnects and Packaging*, vol. CR62, pp. 3-34, 1996.
- [5] D. B. Young, J. W. Scott, F. H. Peters, M. G. Peters, M. L. Majewski, B. J. Thibeault, S. W. Corzine, and L. A. Coldren, "Enhanced Performance of Offset-Gain High-Barrier Vertical-Cavity Surface-Emitting Lasers," *IEEE J. of Quantum Electronics*, vol. 29, no. 6, pp. 2013-2021, 1993.
- [6] K. L. Lear, Internal Communication
- [7] K. D. Choquette, Internal Communication
- [8] B. H. Rose, "Monolithic, Series Connected GaAs Photovoltaic Power Converters for Optoelectronic Component Applications," Albuquerque, NM: Sandia National Laboratories Report Number SAND92-1534, 1992.
- [9] Photonic Power Systems: Mountain View, CA., "Photovoltaic Power Converter Model PPC-6E Data Sheet", 1996.
- [10] Spectra Diode Laboratories: San Jose, CA, "1995 Product Catalog", 1995.
- [11] Y. C. Lee and N. Basavanahally, "Solder Engineering for Optoelectronic Packaging," *Journal of Metals*, vol. 46, no. 6, pp. 46-50, 1994.
- [12] Q. Tan and Y. C. Lee, "Soldering Technology for Optoelectronic Packaging," *Proc. of the 46th Electronic Components and Technology Conference*, pp. 26-36, May 28-31, 1996.

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