

Optoelectronic Subcarrier for Chip-to-Chip Optical PCB Applications Using Long Wavelength VCSELs

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Abstract—An interconnection scheme for chip-to-chip optical link has been proposed in this work where the silicon substrate of the driver integrated circuit (IC) is used as a subcarrier and also as a light path. This interconnection scheme uses a low loss high speed reconfigurable optical printed circuit board (REOPCB) for coupling light from one chip to the other. A multichip transmitter module has been fabricated with a 1 x 4 top-emitting long wavelength (1310 nm) VCSEL array integrated on it. The driver IC is fabricated in a 0.18 μm Si-CMOS technology with a chip size of 1.1 mm x 1.2 mm x 0.322 mm. 72% of the emitted light from the VCSEL is achieved after transmission through the silicon substrate.

Keywords— Multichip module, flip-chip bonding, optical interconnection, optical printed circuit board (OPCB)

I. INTRODUCTION

Optical interconnection technology is one of the potential technologies for meeting with the high speed and bandwidth requirements of next generation computer systems. This is due to the numerous advantages of optical interconnects over electrical interconnects such as higher bandwidth, lower inter-channel crosstalk, and lower power consumption [1], [2]. The increase in the demand of high speed devices has resulted to substantial improvements in integrated circuit technology where new forms of interconnect and packaging technologies such as multi-chip modules come into play [3]. Multichip module technology plays an important role in optical communications components and in particular, multichip transmitter modules are attractive for optical PCB applications due to better electrical performances and reduced size over other packaging structures [4], [5]. Short wavelength VCSELs of about 980 nm have been demonstrated for chip-to-chip optical interconnection using free space optical interconnection with diffractive microlens on two layer stacked silicon (Si) substrates with laser drilled via holes [6]. Silicon substrate offers solution for hybrid modules in microwave and optical engineering because of its advantages such as mature fabrication technology, excellent planarity for flip-chip bonding, multi-interconnect metal layers, good thermal conductivity [7], easiness of making structures (such as V-groove for aligning optical elements) [8], and optical transparency for long wavelengths (above 1 μm). Thus the silicon substrate provides an excellent platform for flip-chip

bonding and can also be utilized as a path for optical transmission.

In this paper, we examine the use of the driver IC of a transmitter module as light path for optical chip-to-chip interconnections. A multichip transmitter module (MCM) using long wavelength (1310 nm) VCSEL array is prepared for chip-to-chip optical interconnects. The transmitter module utilizes its silicon substrate as the medium for light path. The optical characteristics of the silicon substrate of the transmitter module is optimized to minimize optical loss in the area where emitted beam from the VCSEL array passes through. An interconnection scheme that uses a REOPCB is proposed for low loss and high speed chip-to-chip optical interconnect. The transmitter module is packaged in the low loss high speed REOPCB for direct coupling of light from the VCSEL, through the silicon chip, and then to the fiber. The REOPCB is designed as a sub-board which can be passively docked and undocked from the main printed circuit board (PCB).

II. DESIGN OF THE OPTOELECTRONIC SUBCARRIER

The driver IC of the transmitter module is designed and fabricated in a 0.18 μm Si-CMOS technology. It has 4 channels with -3 db bandwidth of 3.6 GHz and operates up to 5 Gbps per channel. The driver chip has a size of 1.1 mm x 1.2 mm x 0.322 mm. Due to the high refractive index of silicon (3.42), only 53% of light can pass through uncoated substrate and anti-reflective coatings on the surfaces can increase light power penetration to about 96%. This is the case for 200-600 μm thick silicon substrate [9]. An area of the driver IC is optimized for light transmission as shown in Figure 1. The silicon nitride/silicon dioxide coating of the driver IC is etched out at the region between the contact pads. The etched region is polished and then covered with anti-reflection (AR) coating in order to minimize loss as light passes through the driver IC. Both sides of the light path region are polished and the anti-reflection coating is placed both on the top and bottom sides of the driver IC.

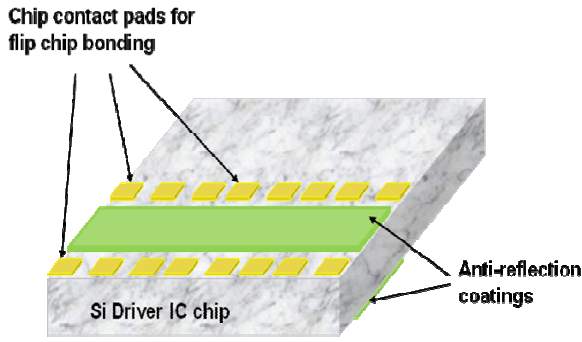


Figure 1. Driver chip showing optimized region with anti-reflection coatings.

The conventional multichip module uses a bottom-emitting VCSEL array where fiber is coupled directly to the VCSEL but is faced down in order to couple light to the fiber array. Our module uses a 1x4 top-emitting long wavelength (1310 nm) VCSEL array was flip-chip bonded to the driver IC using solder balls to make contacts at the chip contact pads. Flip-chip bonding was done at 250 °C at a very low pressure below 150 g/mm² because of the weak InP. The VCSEL has a threshold current and voltage of 1.4 mA and 1.7 V respectively. Figure 2 shows the flip-chip bonded VCSEL on the driver IC.



Figure 2. MCM module showing vertical thickness

To optimize the light yield through the silicon substrate, we studied two structures of the silicon subcarrier; (a) with the silicon dioxide/nitride layer etched out, and (b) without etching out the silicon dioxide layer. Light intensity is determined as light rays from the VCSEL passes through the Air-Chip-Air media. Due to the varying refractive indices of the material layers, the speed and divergence angle of the light rays will vary too. Figure 3 shows the cross section of the layers and Figure 4 shows the gradient index model of the media through which light rays from the VCSEL will pass before it reaches the waveguide.

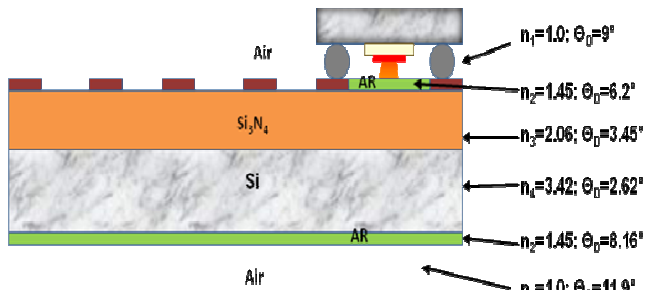


Figure 3. Cross-section of the layers showing the refractive indices and divergence angles for each of the media

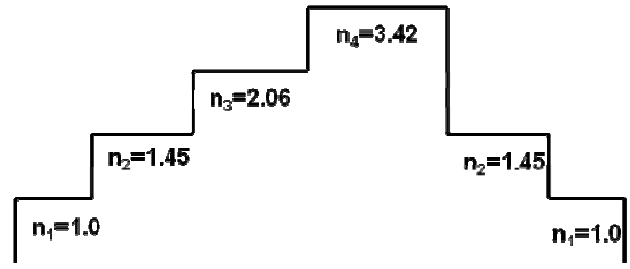


Figure 4. Gradient index model of the media

In order to calculate the light intensity, the concept of pointing vector S is utilized. Pointing vector is the time rate of flow of electromagnetic energy per unit area (i.e. the power intensity)

$$S = E \times H \quad (1)$$

Where E is the electric field vector and H is the magnetic field vector. We'll also apply the concept of boundary conditions that states that the tangential components of E and H are continuous across the boundary.

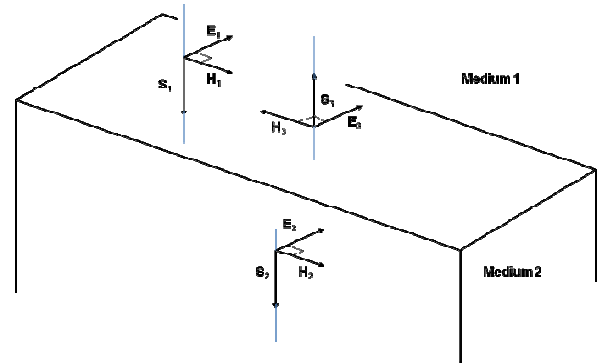


Figure 5. Transmission and reflection coefficients at an interface between two media

Where S_1 , S_2 , and S_3 represent incident ray, transmitted ray, and reflected ray respectively.

$$E_1 + E_3 = E_2 \quad (2)$$

$$H_1 - H_3 = H_2 \quad (3)$$

$$r_E = r_H = \frac{E_3}{E_1} = \frac{H_3}{H_1} = \frac{n_1 - n_2}{n_1 + n_2} \quad (4)$$

$$t_E = \frac{2n_1}{n_1 + n_2} \quad (5)$$

$$t_H = \frac{2n_2}{n_1 + n_2} \quad (6)$$

$$R = \frac{|S_3|}{|S_1|} = |r_E|^2 = |r_H|^2 \quad (7)$$

$$T = \frac{S_2}{S_1} = \frac{n_2}{n_1} |r_H|^2 \approx \frac{n_1}{n_2} |t_E|^2 \quad (8)$$

r and t represent reflection and transmission coefficients while R and T represents reflectance and transmittance respectively. Using equations 4 – 8, we can calculate the amount of transmitted power (intensity) and reflected power. If we do the calculation layer by layer, we'll consider the boundary condition at each interface till the final medium (Air) before the waveguide. Figures 6 and 7 show the cross-sectional profile for the two cases. Tables 1 and 2 show the transmitted and reflected power at each interface for the two cases.

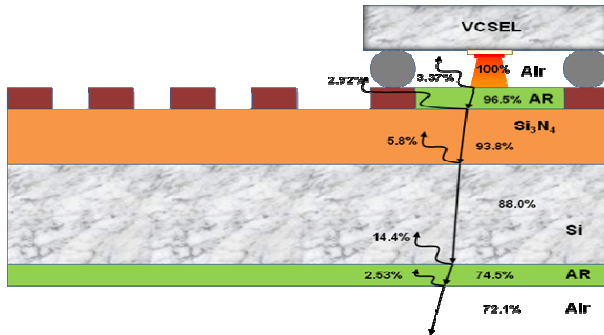


Figure 6. Cross-sectional profile showing transmitted and reflected power as light passes through the chip

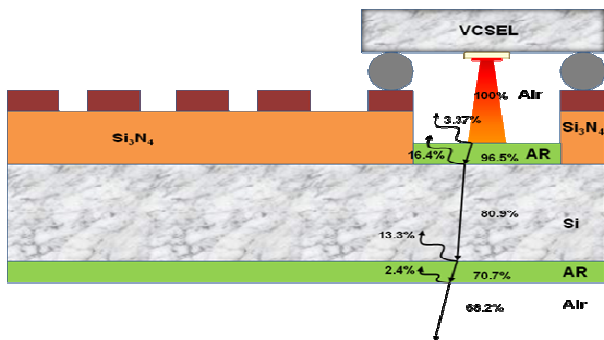


Figure 7. Cross-sectional profile showing transmitted and reflected power as light passes through the chip with the silicon nitride layer etched out

TABLE 1. TRANSMITTED AND REFLECTED POWER PROFILE THROUGH THE DRIVER IC WITH SILICON NITRIDE LAYER

Interface	Transmitted power, T	Reflected power, R
Air – AR	96.5%	3.37%
AR - Si ₃ N ₄	93.8%	2.92%
Si ₃ N ₄ - Si	88.0%	5.8%
Si - AR	74.52%	14.4%
AR - Air	72.1%	2.53%

TABLE 2. TRANSMITTED AND REFLECTED POWER PROFILE THROUGH THE DRIVER IC WITHOUT SILICON NITRIDE LAYER

Interface	Transmitted power, T	Reflected power, R
Air – AR	96.5%	3.37%
AR - Si	80.9%	16.4%
Si - AR	70.7%	13.3%
AR - Air	68.2%	2.4%

From the table it can be seen that the module with the silicon dioxide layer gives a better transmitted optical intensity of 72.1% when compared to the module with the SiO₂ etched out with transmitted optical intensity of 68.2%. This is due to the gradient index profile provided when the SiO₂ is intact.

III. INTERCONNECTION ARCHITECTURE

Our optical interconnection architecture uses an OPCB designed as a sub-board which can be passively docked and undocked from the main printed circuit board (PCB). The sub-board isolates the optical link from the main PCB which makes it easier to troubleshoot problems related to the optical link. It also makes it possible to upgrade the optical link for bi-directional transmission and for denser communication possibilities. The sub-board is therefore referred to as a reconfigurable OPCB (REOPCB) as shown in Figure 8.

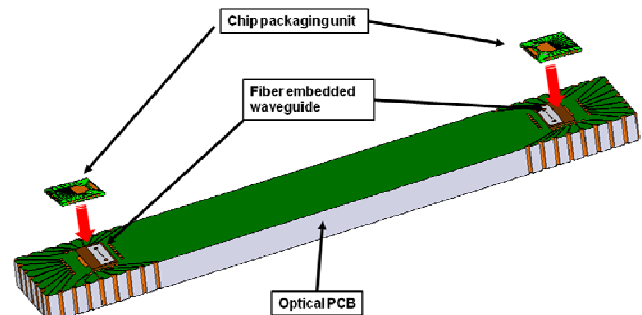


Figure 8. The assembled REOPCB unit

The transmitter module was marked using developer for alignment to the fiber array waveguide. Electrical connections between the module and the IC packaging unit were made using gold wires. The wires were made as short as possible to reduce crosstalk. Fig. 9 shows the packaged module on the waveguide. The OPCB is made of a low loss Rogers ceramic board with dielectric constant of 6.2 at 10 GHz. The REOPCB is connected to the main board using solder balls.

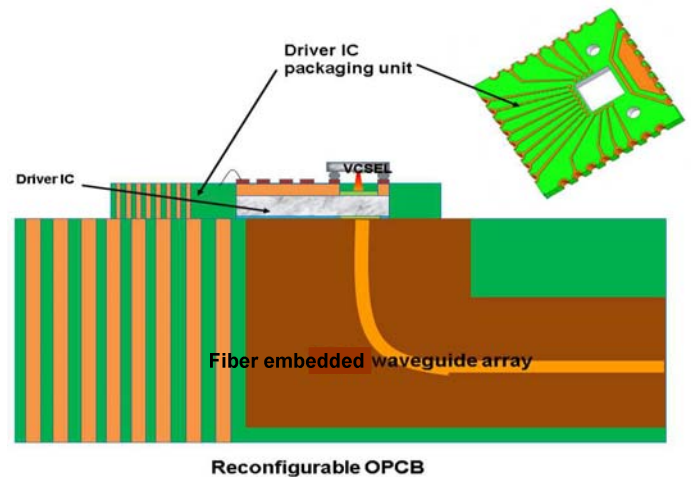


Figure 9. The optical interconnection structure showing the packaged structures

IV. CONCLUSIONS

A multichip transmitter module using a flip-chip bonded 1x4 long wavelength (1310nm) top-emitting VCSEL array was designed and fabricated. The module was packaged in a low loss high speed reconfigurable optical printed circuit board (REOPCB). The module showed a good performance of light intensity of 72% when the SiO₂ layer is not removed. The module can be applied for high speed memory to CPU interconnects.

ACKNOWLEDGMENT

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