The Effect of the Higher Order Modes on the Optical Crosstalk in Free-Space Optical Interconnect

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***Abstract*— In this paper we investigate the effect of the crosstalk introduced due to laser beam imaging in a free-space optical interconnect (FSOI) system. Due to the overfill of the transmitter microlens array by the vertical-cavity surface-emitting laser (VCSEL) beam, one part of the signal is imaged by the adjacent microlens to another channel, possibly far from the intended one. Furthermore, it is known that in practice, VCSELs tend to operate in several transverse modes simultaneously. This will cause even more increase in the interchannel and intersymbol interference, to our knowledge this issue has been neglected so far. The numerical simulation has been performed using a combination of exact ray tracing and the beam propagation methods. The results show that the stray-light crosstalk will increase significantly with either greater system density or higher order modes. The diffraction-caused crosstalk is mainly affected primarily by interconnection distance, channel density.**

Keywords-Stray-light crosstalk; diffraction; free-space optical interconnect

I. Introduction

Performance requirements of short-distance digital communication links have increased considerably with the escalating demand for high speed and high density data links. However, large scale electronic systems are suffering from an interconnection bottleneck due to the inductance and capacitance inherent in electric interconnects [1]. The high bandwidth and channel density achievable by optical interconnects (OIs) make them ideal replacement for electrical interconnects. Optical interconnects also have low power consumption, and can facilitate novel designs of VLSI and parallel optoelectronic systems [2, 3]. Recent developments in the integration of vertical-cavity surface-emitting lasers (VCSELs) arrays with electronic circuitry have increased the potential of optical interconnects [4].

Free-space optical interconnects (FSOIs) have great potential for both chip and board-level interconnection. Several interconnect designs based on array of VCSELs have been proposed [5-8]. From these studies, it is evident that one of the major factors that determines the maximum channel density and signal-to-noise ratio is the optical crosstalk noise within the system. Furthermore, as the microlens diameter decreases to allow for higher interconnect density, the performance of the system will be limited by diffraction.

The most generic implementation of a parallel FSOI system consists of two microlens arrays, employed to collimate and focus the laser beams to an array of photodetectors. The power which is correctly transmitted to its intended receiver is the signal, and the portion of the beam which trespasses on neighbouring channels is the crosstalk noise, Fig. 1. Petrovic *et al* .[9] modelled this crosstalk by calculating the power incident on unintended receiver microlenses due to diffraction at the transmitter microlenses and the dispersive propagation of the laser beam between the transmitter microlens array and the receiver microlens array. Like many other diffraction studies [8, 10], this model ignores the fraction of power that does not travel through the intended transmitter microlens.

However, the fraction of power ignored by the previous studies can be imaged by the neighbouring transmitter microlens to other channels, possibly far from the intended one. This introduces a different kind of crosstalk which will be referred to as stray-light crosstalk in this article, indicated by the dotted area in Fig. 1. To the best of the authors' knowledge this type of crosstalk has not yet been investigated.

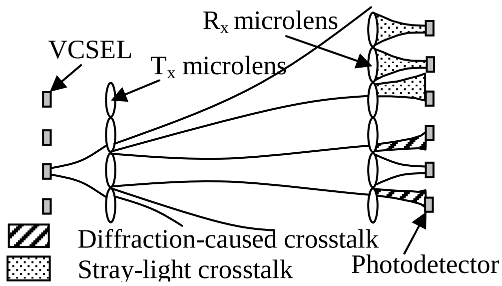

Figure 1. The schematic of free-space optical interconnect showing the diffraction-caused and stray light crosstalk

In practice, vertical-cavity surface-emitting lasers (VCSELs) tend to operate in several transverse modes simultaneously. While most of the published studies discuss the issue of crosstalk considering the fundamental mode alone, the presence of higher order modes will cause a significant degradation in signal to noise ratio in the OI channel.

This paper investigates stray-light crosstalk in microchannel architectures including the effect of higher order modes. In Sec. 2, the FSOI simulation model is developed. Experiments performed on a commercial oxide-confined VCSEL are described in Sec. 3. These experimental findings are used to simulate and compare diffraction-caused and stray-light crosstalk in Sec. 4 and will concluded with a brief discussion in Sec. 5.

II. MICROCHANNEL FSOI DESIGN DESCRIPTION

A. Design Outline

Figure 2 shows the basic architecture used in the simulations: a microchannel FSOI constructed from two microlens arrays, a VCSEL array, and a photodetector array. The VCSEL array is located at $z = 0$, and the first microlens array is situated at $z = d_1$. The second microlens array is at a distance of $d_2 + d_3$ away from the first microlens array, and the photodetector array is positioned $d_4 = d_1$ away from the second microlens resulting in a symmetrical configuration. The pitch of the system is Δ, and the diameter of the microlens is *D*. The fill factor, β, is defined as the ratio of the microlens diameter to the array pitch: β = *D*/Δ. Two metrics frequently used to assess interconnect performance are the maximum achievable channel density, $1/\Delta^2$, and the interconnect length, $L = d_1+d_2+d_3+d_4$.

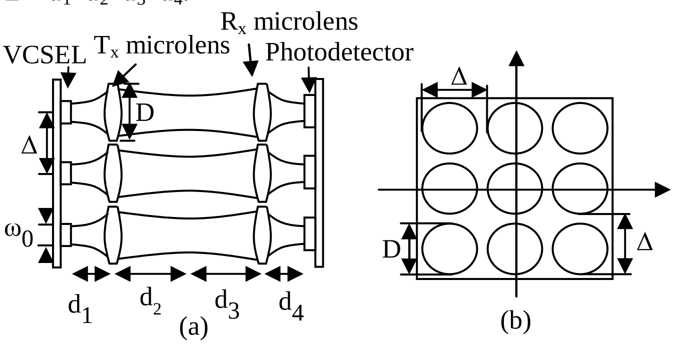

Figure 2. (a) Schematic of a microchannel free-space optical interconnect. (b) Structure of the T_x or R_x microlens array with x-y axis

B. Diffraction-cuased Crosstalk

For each channel, the laser beam of beam waist, ω_0, is emitted from the transmitter plane to its corresponding transmitter microlens and imaged to the intermediate beam waist. The beam propagates from the intermediate beam waist to the intended receiver microlens. We assume that the complete signal power incident on the receiver microlens is focused onto its respective photodetector. Due to the diffraction-caused spreading of laser beams, the beam radius at the receiver microlens frequently exceeds the radius of the receiver microlens itself. Therefore, a fraction of the power incident onto the receiver microlens array will fall on the microlenses adjacent to the intended microlens, the central channel in Fig 1. Optical power incident upon the lenses surrounding the intended lens is the crosstalk noise power in these channels and is usually assumed to be the dominant component of the optical crosstalk noise. In this article we will refer to it as the diffraction-caused crosstalk noise (DCCN).

C. Stray-light Crosstalk

Here we introduce another source of optical crosstalk that, to the best of our knowledge, has not been investigated so far. Again, we consider an arbitrary channel within the microchannel architecture, depicted by Fig 1. In this case, we concentrate on the fraction of power emitted by the VCSEL that falls on the transmitter microlenses adjacent to the intended transmitter lens. Due to the curvature of the microlenses, the beam is refracted away from the intended channel as shown in Fig 1. As it propagates through the system, the beam will further expand until it reaches the receiver microlens plane. Unlike the diffraction caused crosstalk, where most of the noise can be attributed to the adjacent channels, the beam can be redirected to photodetectors far from the intended channel. In this study we demonstrate that, once stray-light crosstalk is properly accounted for, significant crosstalk can be introduced to a receiver by non-neighbouring channels. This type of crosstalk, caused by the overfill of the transmitter microlens, will be referred to as stray-light crosstalk noise (SLCN) throughout this article.

III. HIGHER ORDER TRANSVERSE MODES

For drive currents above threshold, VCSELs typically operate simultaneously in several higher-order transverse modes. In addition to lasing at a slightly different wavelength, these transverse modes propagate with a larger spot size than the fundamental mode and diverge more quickly. The modal composition of a VCSEL is, therefore, an important consideration when attempting to calculate the crosstalk noise in an optical interconnect.

The beam profiles of the transverse modes can be described by two families of orthogonal solutions to the paraxial wave equation: the Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) modes. The LG profiles, expressed in cylindrical coordinates, are the most appropriate representation for our purposes and are presented below [10]:

$$\begin{Bmatrix} \psi_{nm}(r,\theta,z) \\ \psi_{nm}{}^{*}(r,\theta,z) \end{Bmatrix} = K_{nm}\left(\frac{r\sqrt{2}}{w(z)}\right)^{m} L_n{}^{(m)}\left(\frac{2r^2}{w(z)^2}\right) \exp\left(\frac{-r^2}{w(z)^2} - j\frac{kr^2}{2R(z)}\right)\begin{Bmatrix}\cos(m\theta)\\ \sin(m\theta)\end{Bmatrix} \quad (1)$$

where,

$$K_{nm} = A_{nm}N_{nm} \quad (2)$$

and,

$$A_{nm} = \exp\left\{ j\left[(2n+m+1)\arctan\frac{\lambda(z-z_s)}{\pi w_s{}^2} - k(z-z_s)\right]\right\} \quad (3)$$

and,

$$N_{nm} = \frac{2}{w(z)\sqrt{\pi(1+\delta_{om})}}\left[\frac{n!}{(n+m)!}\right]^{1/2} \quad (4)$$

In the above equations, the wave number $k = 2\pi/\lambda$, and the Rayleigh range is given as $z_R = ½k\, w_s^2$, where w_s is the beam waist and is located at $z = z_s = 0$. The beam radius at any distance along the propagation axis is given as:

$$w(z) = w_s \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad (5)$$

the radius of curvature is,

$$R(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right] \quad (6)$$

Equation (3) shows the Guoy phase shift experienced by the laser beams. Higher-order modes (n, $m > 0$) will experience a greater phase shift than the fundamental Gaussian mode, and will resonate at shorter wavelengths inside a cavity. This explains the spectral separation of transverse modes in a laser.

In order to examine the effect of transverse modes, it is necessary to determine the modal content of practical devices. Experiments were performed on a commercially available VCSEL (*Mode 8085-2008*). The continuous-wave, room temperature optical spectra were measured at drive currents up to $7\times I_{th}$, at intervals of 0.05 mA. From this data, the evolution of the VCSEL spectrum was examined and a modally resolved light-current curve was constructed.

From the spectra, the presence and relative power of higher order modes can be observed, but their spatial profiles can not be identified. To accomplish this, an actuator controlled fibre probe was used to scan a cross section of the magnified near field of the laser beam. At each point of a 15×15 grid, the spectrum was recorded, and the modal peaks were isolated. From these measurements we determined the optical power associated with each individual mode at each spatial pixel. The dominant lasing modes of this VCSEL can be identified as: LG_{00}, LG_{01}, LG_{01}^*, LG_{02}, and an LG_{10} + LG_{02} combination.

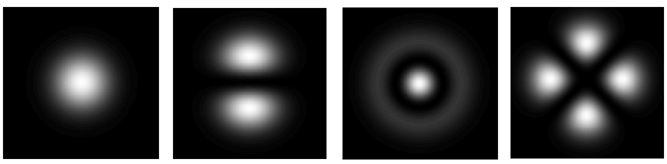

Figure 3. Mode patterns of Laguerre-Gaussian modes

IV. SIMULATION RESULTS

Commercial simulation software, Code V, is used to simulate both the stray-light and diffraction-caused crosstalk. The design parameters used for simulation are as follows: the pitch between the channels is 250 µm, the beam has a waist radius of 3 µm and a central wavelength of 850 nm. The transmitter and receiver microlenses are assumed to be spherical lenses, made from BK7 optical glass, with a 95% fill factor. The focal length of all microlenses is 800 µm and the distance between the VCSEL and the transmitter microlens is fixed at $d_1 = f + z_R$, where f is the microlens focal length, and z_R is the Rayleigh range. Both the stray-light and diffraction-caused crosstalk noise are measured by the optical power incident upon unintended receiver micolenses. It is assumed that all power that falls on a receiver microlens will be detected by its receiver. The simulation was performed on a two-dimensional, lattice microlens array of 64×64 channels.

Optical interconnect designs are typically evaluated by considering the propagation of point sources or from the uniform surface emitters. To determine the effect of higher order transverse modes on FSOI performance, we propagate a two-dimensional beam profile through the optical system. The extended sources used in these simulation experiments are based on the experimentally determined modal structure of the VCSEL beams measured in Sec. 3. and are formed by the weighted combination of the following Laguerre-Gaussian modes: LG_{00}, LG_{01}, LG_{01}^*, LG_{10}, and LG_{20}. The mode patterns used in the simulation are shown in Fig 3. For each mode, the calculated transverse profile is mapped onto a 101×101 point computational grid used as the beam definition for the diffraction-based beam propagation. A combination of geometrical ray tracing and diffraction-based propagation techniques are used to trace the beam through the optical interconnect.

Figure 4 shows the normalised stray-light crosstalk noise for different transverse modes with increasing channel density. The stray-light crosstalk noise increases with channel density, and interconnect performance degrades further with the presence of higher order modes. More interesting results are obtained by examining the stray light crosstalk noise for different interconnect lengths (Fig. 5). Unlike the diffraction caused crosstalk, the stray-light crosstalk noise remains relatively constant with increasing interconnect length and actually decreases slightly as the stray light is refracted outside the receiving area of the photodetector array. This trend sharply contrasts with diffraction caused crosstalk, which increases significantly with channel length.

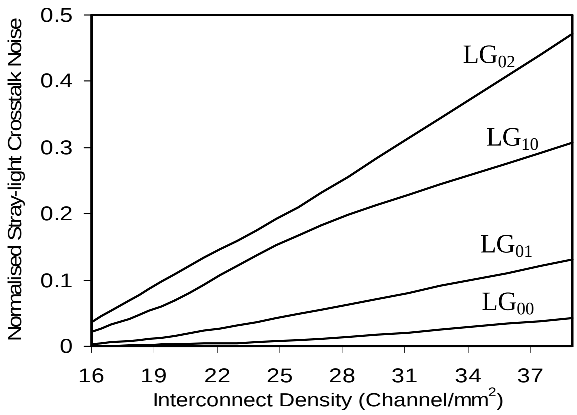

Figure 4. Stray-light crosstalk noise in both graphs is normalised to the power of the emitted beam: Normalised Stray-light crosstalk noise with increasing system capacity (channels per mm^2) for different modes.

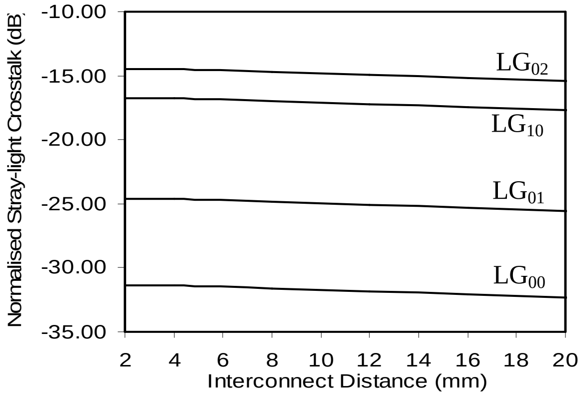

Figure 5. Stray-light crosstalk noise is normalised to the power of the emitted beam and then calculated using a log scale: Normalised Stray-light crosstalk noise with increasing interconnection distance for different modes.

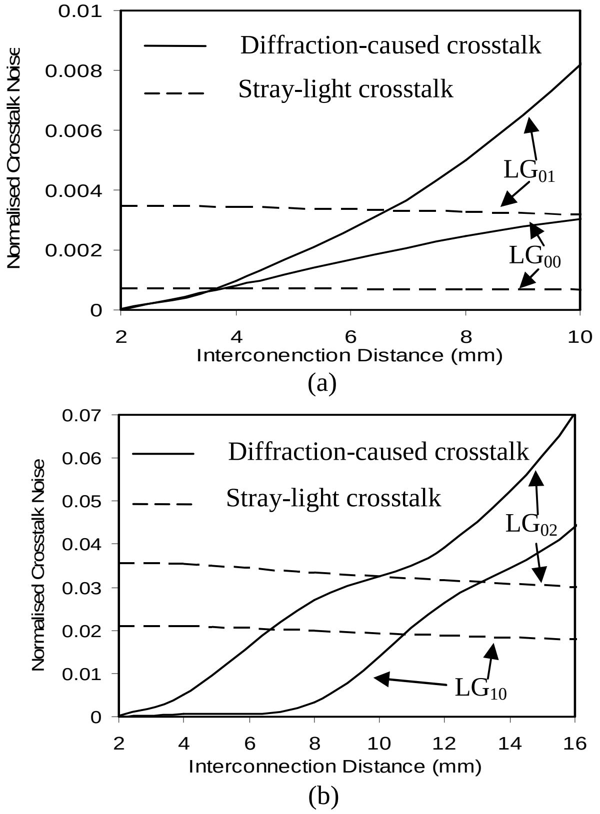

Figure 6. Diffraction-caused and stray-light crosstalk noise in both graphs is normalised to the power of the emitted beam: (a) Comparison of normalised diffraction-caused and stray-light crosstalk noise with increasing interconnection distance for LG_{00} and LG_{01}. (b) Comparison of normalised diffraction-caused and stray-light crosstalk noise with increasing interconnection distance for LG_{10} and LG_{02} modes.

The effect of diffraction caused crosstalk and stray light crosstalk noise is compared in Figs. 6(a) and 6(b). A channel pitch of 250 µm was maintained as the interconnect length was increased, and several transverse modes were propagated through the interconnect. The transition channel lengths were 3 mm, 6.5 mm, 10.5 mm, and 11 mm for the LG_{00}, LG_{01}, LG_{02}, and LG_{10} modes respectively. It can be said that stray-light crosstalk occurs at the transmitter lens and is dictated by channel density and beam spot size, while diffraction-caused crosstalk occurs over the length of the channel and will be affected by length and density primarily.

V. Conclusion

For the first time, to the authors' knowledge, the effect of stray-light crosstalk noise on free-space optical interconnects has been investigated. A numerical simulation was used in conjunction with an experimental investigation to evaluate the optical noise introduced at the transmitter microlens by multimode VCSEL beams. The stray light crosstalk noise was found to be significant compared to diffraction caused crosstalk noise; particularly for short, high channel density interconnects. Both forms of crosstalk noise are strongly affected by the presence of higher order transverse modes.

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