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Bessel beams and Gaussian beams as information carriers in free space optical interconnects systems: a comparison study

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ABSTRACT

We introduce models for crosstalk estimation in a lens-based free space optical interconnects that use non-diffracting Bessel beams and Gaussian beams. We perform a comparison study for the performance two systems. The optical field at the detector plane was derived for the two beam profiles. In both cases the expressions for the output optical filed are expressed in terms of complex Gaussian functions. The performance of the system for the two beams is evaluated and compared. Using simulation results we show that the use of Bessel beam gives superior results to that of using Gaussian beam for large interconnects distance.

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1. INTRODUCTION

Light propagation diffraction is considered as one of the important problems that affects the performance of free space optical interconnects (FSOIs) systems, namely, the signal-to-crosstalk ratio [1-5]. In these FSOIs systems light sources with Gaussian profiles are usually used. The crosstalk in these Gaussian-based systems is prominent and careful design is required to reduce its effect [6-9]. One interesting method to reduce the diffraction, particularly in board-to board applications with large interconnect distance, is the use of non-diffracting Bessel beams [10-12]. In [10] an efficient conversion of light from a laser diode into a Bessel beam whose axial intensity varies almost uniformly with distance using only a holographic optical element is explained. An interesting shadowing of the Bessel beam is demonstrated where on blocking the intense central spot the propagating ring pattern acts to reform the central spot a short distance after the obstruction. This behavior together with the long propagation range for the Bessel beam's central spot are considered for multi-board optical interconnects.

In [11] authors present high-density pseudo-non-diffracting beam arrays produced by using holographic method. The demonstrated pseudo-non-diffracting beams can keep their central spot size of about 95 μm within a distance of 40 cm. The center-to-center beam separation is 250 μm, which is much smaller than those achieved by collimated Gaussian beams with the same interconnect range. The small central lobe sizes can further avoid the use of collection/focusing lenses at the high-speed photodetector receivers. The concept of using non-diffracting beam in a lensless free space optical interconnects was investigated in [12]. It was shown that the performance of the FSOIs system using non-diffracting beams outperforms that which uses Gaussian beams especially for large interconnects distance. However, it was explained that the side lobes of the Bessel beams overlap with the neighbor channels and increase the crosstalk. Most of the work presented in the literature regarding the use of nondiffrating Bessel beams was based on some experimental demonstration. In fact, modelling the crosstalk in these systems is necessary for the design and for the sake of finding solutions and methods to reduce crosstalk.

In this article, we introduce models for crosstalk estimation for the optical interconnect system that use non-diffracting Bessel beams in a lens-based free space optical interconnects. Closed form expressions for the light intensity distribution at the detector plane are derived for Gaussian and Bessel beams the by expanding the micro-lens aperture in term complex Gaussian functions. Using these expressions, the signal to crosstalk ratio is evaluated and used as a performance measure. A comparison study is performed between the system that uses the Bessel beam and the one that uses the Gaussian beams.

The main goals of this paper is to (1) introduce crosstalk model for nondifffacting beam based free space optical interconnects systems (2) compare the interconnect performance using these beams with that of Gaussian beam based systems (3) Recommend one of these systems for a given application.

2. OUTPUT OPTICAL FIELD USING DIFFRACTION INTEGRAL

The lens system considered in this paper is shown in Figure 1. This system contains VCSELs array, lens array, and detectors array located at the output plane.

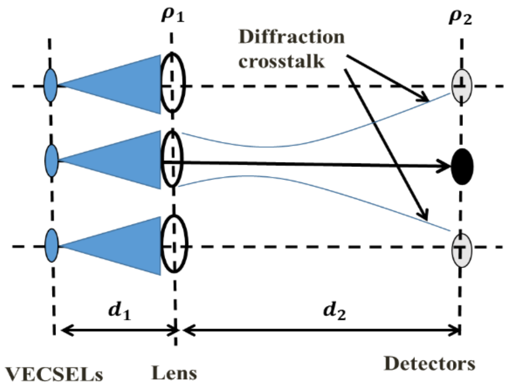

Figure 1. Micro-lens based FSOIs

The input plane is the plane $\rho = \rho_1$ and the output plane is the plane $\rho = \rho_2$. The distance between these two planes is d_2. The light sources (VCSELs) array is placed at the front focal length of the lens. For an input optical field $E_1(\rho_1, \theta_1)$, the output optical field $E_2(\rho_2, \theta_2)$ can be found using Collins diffraction integral as follows [13].

$$E_2(\rho_2, \theta_2) = \frac{ik}{2\pi b} \int_0^{\infty} \int_0^{2\pi} E_1(\rho_1, \theta_1) A(\rho_1) \times \exp\left[-\frac{ika}{2b}\rho_1^2 - \frac{idk}{2b}\rho_2^2 + \frac{ik\rho_1\rho_2}{b}\cos(\theta_1 - \theta_2) \right] \rho_1 d\rho_1 d\theta_1 \tag{1}$$

ρ_1, θ_1 and ρ_2, θ_2 are the cylindrical coordinates. $A(\rho_1)$ is the lens' aperture function. $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength. *a*, *b*, *c*, and *d* are the transfer matrix elements of the FSOIs system and are given by:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 - \left(\frac{d_2}{d_1}\right) & d_2 \\ \frac{-1}{d_1} & 1 \end{bmatrix} \tag{2}$$

3. OUTPUT OPTICAL FIELD FOR GAUSSIAN INPUT BEAM

Assuming Gaussian model for the input optical field, $E_1(\rho_1,\theta_1)$ can be written as

$$\mathrm{E}_1(\rho_1,\theta_1) = \exp\left[-\frac{\rho_1^2}{\omega_1^2}\right] \tag{3}$$

ω_1 the beam radius at the front surface of the lens and is given by

$$\omega_1 = \omega_0 \sqrt{1+\frac{\lambda^2 d_1^{\ 2}}{\pi^2 \omega_0^4}} \tag{4}$$

ω_0 is the waist radius of the VCSEL's beam. The integral in (1) can be evaluated by using (3) and recalling integral formula

$$J_0(x) = \frac{1}{2\pi}\int_0^{2\pi} \exp(ix\cos\theta)d\theta \tag{5}$$

to obtain

$$E_2(\rho_2) = \frac{ik}{b}\exp\left(-\frac{ikd\rho_2^2}{2b}\right)\int_0^{\infty}\exp\left(-\rho_1^2/q^2\right)J_0\left(\frac{k\rho_2}{b}\rho_1\right)A(\rho_1)\rho_1 d\rho_1 \tag{6}$$

For a circular lens with a_1 radius, the aperture function is given by

$$A(\rho_1) = \begin{cases} 1 & \rho_1 \le a_1 \\ 0 & \rho_1 \succ a_1 \end{cases} \tag{7}$$

Substituting in (7) for $A(\rho_1)$ from (8), to obtain

$$E_2(\rho_2) = \frac{ik}{b}\exp\left(-\frac{ikd\rho_2^2}{2b}\right)\int_0^{a_1}\exp\left(-\rho_1^2/q^2\right)J_0(\alpha\rho_1)\rho_1 d\rho_1 \tag{8}$$

$$\frac{1}{q^2} = \frac{1}{\omega_1^2} + \frac{ika}{2b} \tag{9}$$

$$\alpha = \frac{k\rho_2}{b} \tag{10}$$

Equation (8) is a formula for the output optical field for a Gaussian beam propagating through the lens-based FSOIs system shown in Figure 1. The output optical field can be evaluated in a closed form by expanding the lens' aperture function in terms of complex Gaussian functions [14, 15] as follows

$$A(\rho_1) = \sum_{n=1}^{N} A_n \exp\left(-\frac{B_n}{a_1^2}\rho_1^2\right) \tag{11}$$

where A_n and B_n are the expansion and Gaussian complex coefficients, respectively. The values of these coefficients can be found by optimization-computation directly [14]. On substituting in (8) for $A(\rho_1)$

from (11), to get

$$E_2(\rho_2) = \frac{ik}{b}\exp\left(-\frac{ikd\rho_2^2}{2b}\right)\sum_{n=1}^{N} A_n \int_0^{\infty} \exp\left(-p\rho_1^2\right) J_0(\alpha\rho_1)\rho_1 d\rho_1 \tag{12}$$

$$p = \frac{1}{q^2} + \frac{B_n}{a_1^2} = \frac{1}{\omega_1^2} + \frac{ika}{2b} + \frac{B_n}{a_1^2} \tag{13}$$

The integral in (12) can be solved by recalling the integral formula

$$\int_0^{\infty} \exp(-px) J_0\left(2\sqrt{x}\sqrt{\alpha}\right) dx = p^{-1}\exp\left(-\frac{\alpha}{p}\right) \tag{14}$$

Using the integral in (14), the output optical filed in equation (12) can be expressed as

$$\begin{aligned} E_2(\rho_2) &= \frac{ik}{b}\exp\left(-\frac{ikd\rho_2^2}{2b}\right)\sum_{n=1}^{N} A_n \int_0^{\infty} \exp\left(-p\rho_1^2\right) J_0(\alpha\rho_1)\rho_1 d\rho_1 \\ &= \frac{ik}{b}\exp\left(-\frac{ikd\rho_2^2}{2b}\right)\sum_{n=1}^{N} \frac{A_n}{2p}\exp\left(-\frac{k^2}{4pb^2}\rho_2^2\right) \end{aligned} \tag{15}$$

Equation (15) is an approximate closed form solution for the diffraction integral of equation (8). Note that the solution is written in terms of the elements of the optical system transfer matrix.

4. OUTPUT OPTICAL FIELD FOR BESSEL INPUT BEAM

Assuming a Bessel non-diffracting beam for the input optical filed, $\mathrm{E}_1(\rho_1, \theta_1)$ at the front surface of the microlens can be given by

$$\mathrm{E}_1(\rho_1, \theta_1) = \mathrm{J}_0(\sigma\rho_1) \tag{16}$$

σ is the the transverse wave number which controls the sharpness of the beam. Now, by substituting (16) into (1) and using (11) for the aperture and using the following two integrals

$$\begin{aligned} &\frac{1}{2\pi}\int_0^{2\pi} \exp\left[ix\cos(\theta_2 - \theta_1)\right]\exp\left[-in\theta_1\right] d\theta_1 \\ &= i^n J_n(x)\exp\left[-in\theta_2\right] \end{aligned} \tag{17}$$

$$\begin{aligned} &\int_0^{\infty} \exp\left[-\gamma\rho^2\right] J_n(\alpha\rho) J_n(\beta\rho)\rho d\rho \\ &= \frac{(-1)^n}{2\gamma} \times \exp\left[-\frac{in\pi}{2}\right]\exp\left[-\frac{1}{4\gamma}(\alpha^2 + \beta^2)\right] J_n\left(\frac{i\alpha\beta}{2\gamma}\right) \end{aligned} \tag{18}$$

The optical field at the detectors array can be found as

$$\begin{aligned} &\mathrm{E}_2(\rho_2, \theta_2) = \sum_{n=1}^{N} A_n \frac{k(-1)^n (\mathrm{i})^{\mathrm{n+1}}}{bq}\exp\left[-im\theta_2 + \frac{in\pi}{2}\right] \\ &\exp\left[-\frac{ik}{b}d\rho_2^2\right]\exp\left[-\frac{1}{2q}\left(\sigma^2 + \frac{k^2\rho_2^2}{b^2}\right)\right] J_n\left(i\sigma\frac{k\rho_2}{qb}\right) \end{aligned} \tag{19}$$

$$q = \frac{2B_n}{a_1^2} + \frac{ika}{b} \tag{20}$$

5. CROSSTALK CALCULATIONS

The crosstalk power received by the intended detector can be evaluated as the total power received by all other detectors (excluding the intended detector) from the light passing through the intended lens with only the intended source is on. Taking into account only the eight nearest detectors, the crosstalk power can be expressed as

$$P_c = 4\iint_{A_1} \left|\mathrm{E}_2(\rho_2,\theta_2)\right|^2 \rho_2 d\rho_2 d\theta_2 + 4\iint_{A_2} \left|\mathrm{E}_2(\rho_2,\theta_2)\right|^2 \rho_2 d\rho_2 d\theta_2 \tag{21}$$

A_1 is the area of one of the four neighbor detectors and A_2 is the area of one of the next four neighbor detectors. The signal power is the power received by the intended detector assuming only the intended source is on and is given by:

$$P_s = \iint_{A} \left|\mathrm{E}_2(\rho_2,\theta_2)\right|^2 \rho_2 d\rho_2 d\theta_2 \tag{22}$$

A is the area of the intended detector. Having determined the signal and the crosstalk power, the signal to crosstalk ratio, SCR, can be evaluated as

$$SCR = \frac{P_s}{P_c} \tag{23}$$

6. NUMERICAL SIMULATIONS

In this section we show numerical results to explain the advantages of using the Bessel beam as information carrier in free space optical interconnects. We also include numerical results for the optical system that uses the Gaussian beam as information carrier. In our simulations a wavelength of λ=0.850 µm is assumed for both beams. For the Bessel beam the transverse wave number σ=2.5 $(\mu m)^{-1}$ and a beam radius of 5 µm at the front surface of the lens for the Gaussian beam. The lens has a focal length and a diameter of 720 µm and 300 µm, respectively. The distance between neighboring detectors as well as neighboring light sources is 300 µm. Figure 2 shows the 1-D transverse profiles for the input field intensity for both the Bessel and Gaussian beams. The parameters of the beams are chosen to have almost the same width at the input plane. To show the benefits of using Bessel beam, the SCR versus the detector radius is plotted in Figure 3, 4 and 5 for three different values of interconnects distance. Comparing the three figures, we can see that the SCR for the FSOIs system using Bessel beam outperforms that of the system which uses the Gaussian beam for large interconnects length. In Figure 3 the interconnects length is small and using the Gaussian beam is still preferred since the diffraction can be tolerated. However, as the interconnects length increases the effect of the diffraction is apparent as shown in Figure 4 and Figure 5 and in this case the Bessel beam is preferred.

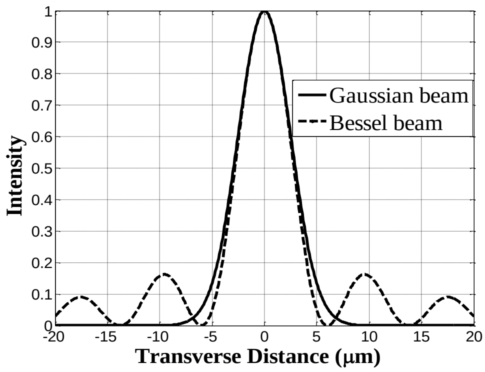

Figure 2. Input optical Field intensity for the two

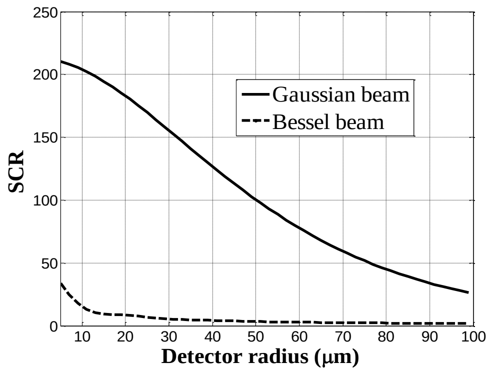

Figure 3. SCR versus detector radius with

beams

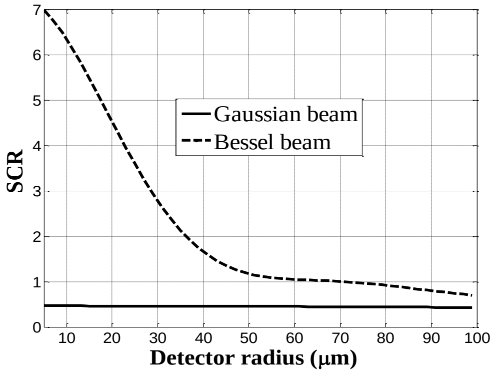

Figure 4. SCR versus detector radius with interconnect length of 8mm

interconnect length of 3 mm

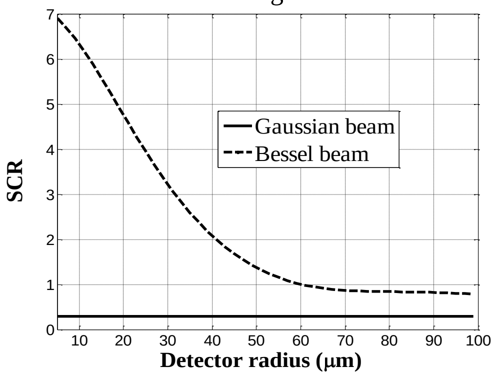

Figure 5. SCR versus detector radius with interconnect length of 10mm

7. CONCLUSION

Crosstalk models for the free space optical interconnects system have been introduced for two systems. The performance of two systems was analyzed using paraxial approximation. One of the optical systems used the Gaussian beam as information carrier and the other system used Bessel beams. Analytical formulas for output optical field at the detector plane were derived and used to evaluate the crosstalk which we used as the performance measure. The simulation results have shown that the use of Bessel beam gave superior results to that of using Gaussian beam at large interconnects lengths. For board-to board interconnects the use of nondiffracting beams is more reliable.

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Nedal Al-Ababneh received his B.Sc. and M.Sc. degrees in Electrical Engineering from Jordan University of Science and Technology in 1993 and 1996 respectively. He received his Doctoral of Engineering degree in Electrical engineering from University of Massachusetts-Lowell (USA) in 2004. He is currently full professor with the department of electrical engineering in Jordan University of Science and Technology. His research interests are in free space optical interconnects and distributed detection systems.