Improvement of misalignment tolerance in free-space optical interconnects

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ABSTRACT

In this paper, the use of micro lenses with non-uniform transmittance apertures as an alternative to those with uniform transmittance apertures in optical communication systems is proposed. In particular, we consider the use of micro lenses with tapered Gaussian transmittance profiles to improve the misalignment tolerance in optical interconnects. We study the effects of utilizing Gaussian transmittance profiles on the propagation of light beams and the signal to crosstalk ratio of misaligned optical systems. Moreover, we consider the use of uniform transmittance profiles in optical systems for the sake of comparison. To this end, the crosstalk optical noise is modeled at the plane of the detectors array considering the two scenarios of uniform and Gaussian apertures. This was possible after finding the optical field for both scenarios at the of the detectors array. Numerical results clearly demonstrate the significant improvement in decreasing the crosstalk and increasing the signal to crosstalk ratio in the considered optical systems upon utilizing the Gaussian profiles.

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1. INTRODUCTION

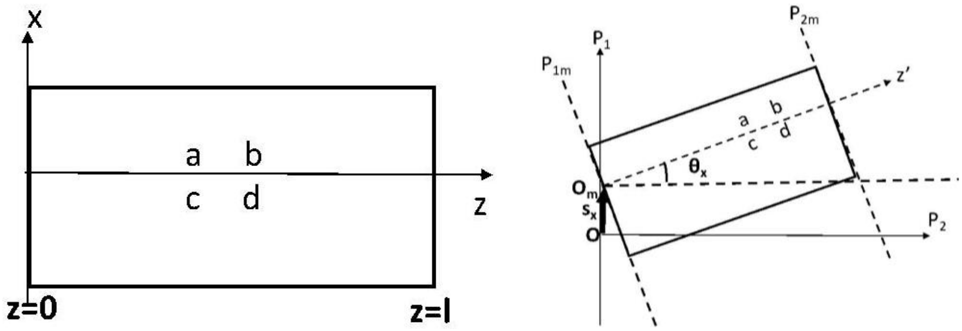
With the large growing demand for data processing and transmission in the current information age, the required data rate per channel increases and more channel bandwidth is required. Free space optical interconnects (FSOIs) present a promising technology that can be used as wideband channels to support the very high data rate transmission in many computing systems [1]–[9]. However, misalignment of different optical components as a result of manufacturing or installation reasons is considered as relevant issue that affects the design and performance of FSOIs systems [10]–[14]. Therefore, studying the impact of misalignment on FSOIs systems and introduce solutions to reduce its effect is essential in these optical systems [15]–[17]. In general, the misalignment of different components in FSOIs increases the optical crosstalk that already exists in these systems. Therefore, methods to deal with crosstalk to increase the system tolerance to misalignment are required. Most of solutions discussed in the literature were created and developed based on presenting optimized models for the crosstalk of the misaligned optical system. For example, in [18]–[20] modifications on the mode expansion model were introduced and optimized in the presence higher transverse operation modes of the laser beam. In [21] the use of Hermite-Gaussian beams and the theory of Collins diffraction were introduced to model the optical diffractions. In [22], the generalized diffraction integral formula assuming a Laguerre-Gaussian (LG) model for the input beam was used to model crosstalk. An approximation formula for the output optical field was obtained in terms of a sum of complex-valued Gaussian models. In [23] a model that uses a micro lens with a Gaussian transmittance profile is used to reduce crosstalk. In this method it was shown that crosstalk can be reduced as a result of reducing the optical power that is coupled to the neighboring channels. Reducing the coupled light might also improve the optical systems' misalignment tolerance, which is the main goal of this paper.

In this paper, we show that the use of a micro lens with Gaussian profile increases the misalignment tolerance in lens based FSOIs. To the extent of authors' knowledge, the use of tapered profile for micro lens transmittance to increase the system's tolerance to misalignment in FSOIs models has not been studied yet. Section 2 demonstrates the research methods investigated and proposed in this study. This includes analyses of a general misaligned optical model and derivations of light irradiance distributions assuming three cases for the micro lenses: an open aperture, a uniform circular aperture, and a Gaussian profile aperture, respectively. In addition, crosstalk calculations are provided for all of the considered cases. In section 3, numerical results and discussion are provided. Finally, the paper is concluded in section 4.

2. METHOD

2.1. A general misaligned optical system

Figure 1 shows a general diagram for a two-dimensional optical model, without misalignment as described in Figure 1(a) and with misalignment as described in Figure 1(b). P_1 and P_2 represent the input and output planes for an optical system without misalignment, on the other hand, P_{1m} and P_{2m} represent the misaligned planes. l is the distance between the input and the output planes along the z-axis. x_1, y_1 and x_2, y_2 indicate the transverse misaligned coordinates at the front surfaces of the input and output planes, respectively.



(a) (b)

Figure 1. Schematic diagram of optical model (a) without misalignment and (b) with misalignment

The output field $E_2(x_2, y_2)$ at the output plane can be obtained by exploiting Collins diffraction integrals as (1):

$$E_2(x_2, y_2) = \frac{ik}{2\pi b}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1(x_1, y_1) \times \exp\left[\frac{-ik}{2b}\begin{pmatrix} a(x_1^2 + y_1^2) - 2(x_1x_2 + y_1y_2) \\ +d(x_2^2 + y_2^2) + ex_1 + fy_1 + gx_2 + hy_2 \end{pmatrix}\right] \mathrm{d}x_1\, \mathrm{d}y_1 \quad (1)$$

where $E_1(x_1, y_1)$, $k = 2\pi/\lambda$, and λ are the input field, wave number, and wavelength, respectively. The elements of the transfer matrix of aligned optical system are *a*, *b*, *c*, and *d*. The misalignment parameters $e, f, g,$ and h are given as (2) to (5):

$$e = 2(\alpha_T s_x + \beta_T \theta_x) \quad (2)$$

$$f = 2(\alpha_T s_y + \beta_T \theta_y) \quad (3)$$

$$g = 2(b\gamma_T - d\alpha_T)s_x + 2(b\delta_T - d\beta_T)\theta_x \quad (4)$$

$$h = 2(b\gamma_T - d\alpha_T)s_y + 2(b\delta_T - d\beta_T)\theta_y \quad (5)$$

The parameters S_x and S_y represent the misalignments in the x and y directions, respectively. θ_x and θ_y represent the angular misalignments. $\alpha_T, \beta_T, \gamma_T$ and δ_T represent the misalignment elements that can be written as (6):

$$\alpha_T = 1 - a, \beta_T = l - b, \gamma_T = -c, \delta_T = 1 - d \tag{6}$$

Assuming $x = \rho\cos(\theta)$ and $y = \rho\sin(\theta)$, the optical field in (1) can be written in cylindrical coordinates for slightly misaligned system as [24]:

$$E_2(\rho_2, \theta_2) = \frac{ik}{2\pi b}\int_0^{\infty}\int_0^{2\pi} E_1(\rho_1, \theta_1)\, exp\left[-\frac{ik}{2b}\rho'^2_2\right] exp\left[\frac{ika}{2b}\rho_1^2\right] \times exp\left[\frac{ik\rho_1}{b}\rho''_2\, cos(\theta_1 - \varphi)\right] \rho_1 d\rho_1 d\theta_1 \tag{7}$$

where ρ_1, θ_1 and ρ_2, θ_2 are the cylindrical coordinates in the misaligned planes, respectively. In addition, ρ_2' and $\rho_2''^2$ are defined as

$$\rho'^2_2 = d\rho_2^2 + g\rho_2 \cos\theta_2 + h\rho_2 \sin\theta_2$$
$$\rho''^2_2 = (\rho_2 \cos\theta_2 - e/2)^2 + (\rho_2 \sin\theta_2 - f/2)^2$$

and

$$\varphi = tan^{-1}\left(\frac{\rho_2 \sin\theta_2 - f/2}{\rho_2 \cos\theta_2 - e/2}\right)$$

2.2. Open aperture misaligned FSOIs

For this section the FSOIs system is shown in Figure 2. An array of vertical cavity surface emitting lasers (VCSELs) is located at the front focal length of an array of micro lenses with focal length of f_t for each. The output plane contains an array of photodetectors. l is the distance between detector and micro lenses arrays. S_x and S_y are the transverse misalignment of the micro lens.

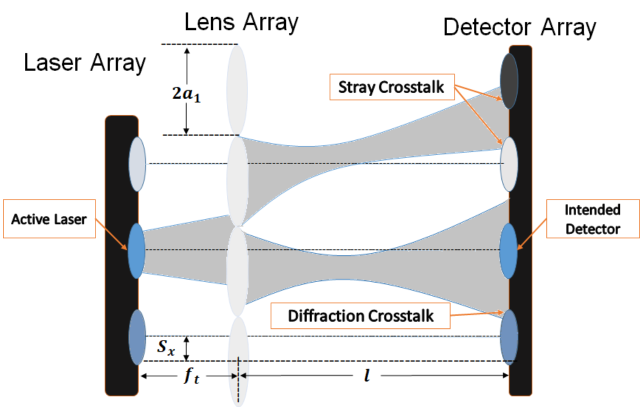


Figure 2. Free space optical system with transverse misalignment

The output field at the detector's plane can be found using (7). Neglecting the angular misalignment ($\theta_x = \theta_y = 0$) the transfer matrix elements are:

$$a = 1 - \left(\frac{l}{f_t}\right), b = l,\ c = -\frac{1}{f_t}, d = 1 \tag{8}$$

and the misalignment parameters are:

$$e = 2\frac{l}{f_t}s_x,\quad f = 2\frac{l}{f_t}s_y,\quad g = 0,\ h = 0 \tag{9}$$

Assuming a LG beam model, the field at the input surface of the microlens can be given by (10):

$$E_1(\rho_1,\theta_1) = \left(\sqrt{2}\frac{\rho_1}{w_1}\right)^m \exp\left[-\frac{\rho_1^2}{w_1^2}\right] \mathrm{L}_p^m\left[2\frac{\rho_1^2}{w_1^2}\right] \times \exp[-im\theta_1] \quad (10)$$

where L_p^m is the Laguerre polynomial [24], [25]. w_1 is the beam radius and is given by [26].

$$w_1 = w_0\sqrt{1+\frac{\lambda^2 f_t^2}{\pi^2 w_0^4}}$$

where w_0 is the LG beam's waist radius.

Using (10) and (7) along with (8) and (9), the optical field at the array of detectors can be formulated as (11):

$$\begin{aligned} E_{2u}(\rho_2,\theta_2) &= \left(\frac{ik}{2l}\right)^{m+1} \exp[-im\theta_2]\exp\left[\frac{ik}{2l}(d\rho_2^2 + g\rho_2\cos\theta_2 + h\rho_2\sin\theta)\right] \\ &\times \left[\frac{ik[1-(l/f_t)]}{2l}+\frac{1}{\omega_1^2}\right]^{-m-p-1}\left[\frac{ik[1-(l/f_t)]}{2l}-\frac{1}{\omega_1^2}\right]^p \\ &\times \left[\frac{\sqrt{2}}{\omega_1}\sqrt{(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2}\right]^m \\ &\times \exp\left[-\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{4l^2\left(\frac{ik[1-(l/f_t)]}{2l}+\frac{1}{\omega_1^2}\right)}\right] \\ &\times L_p^m\left[\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{2\omega_1^2 l^2\left(\frac{k^2[1-(l/f_t)]^2}{4l^2}+\frac{1}{\omega_1^4}\right)}\right] \end{aligned} \quad (11)$$

In the context of slightly misaligned open aperture lens based FSOIs system, (11) represents the optical field irradiance calculated at the array of detectors for the LG beams propagating. Importantly, this equation can be used to estimate the crosstalk in a misaligned open aperture optical system. This is because the equation accounts for the transverse misalignment parameters.

2.3. FSOIs with uniform circular aperture

In this section, we assume the presence of a circular aperture with uniform hard edge transmission profile at the plane of the micro lenses array. Let $A(\rho_1)$ be the uniform hard edge circular aperture function with a_1 radius, then

$$A(\rho_1) = \begin{cases} 1 & \rho_1 \le a_1 \\ 0 & \rho_1 > a_1 \end{cases} \quad (12)$$

In this case, the optical field at the array of detectors is:

$$\begin{aligned} E_{2a}(\rho_2,\theta_2) &= \frac{ik}{2\pi b}\int_0^\infty\int_0^{2\pi} E_1(\rho_1,\theta_1)\,A(\rho_1) \\ &\times exp\left[-\frac{ik}{2b}\rho'^2_2\right] exp\left[\frac{ika}{2b}\rho_1^2\right] \\ &\times exp\left[\frac{ik\rho_1}{b}\rho_2''\,cos(\theta_1-\varphi)\right]\rho_1 d\rho_1 d\theta_1 \end{aligned} \quad (13)$$

The integral in (13) can be found using the following expansion for the aperture function [24]

$$A(\rho_1) = \sum_{n=1}^{N} C_{1n}\exp\left(-\frac{C_{2n}}{a_1^2}\rho_1^2\right) \quad (14)$$

where C_{1n} and C_{2n} are complex coefficients. By substituting (14) into (13) we obtain

$$E_{2a}(\rho_2,\theta_2) = \left(\frac{ik}{2l}\right)^{m+1} \exp[-im\theta_2]\exp\left[\frac{ik}{2l}(d\rho_2^2 + g\rho_2 \cos\theta_2 + h\rho_2 \sin\theta)\right]$$
$$\times \left[\frac{\sqrt{2}}{\omega_1}\sqrt{(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2 \sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2}\right]^m$$
$$\sum_{n=1}^{N} C_{1n}\left[\frac{ik[1-(l/f_t)]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_1^2}\right]^{-m-p-1}$$
$$\times \left[\frac{ik[1-(l/f_t)]}{2l} + \frac{C_{2n}}{a_1^2} - \frac{1}{\omega_1^2}\right]^p$$
$$\times \exp\left[-\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{4l^2\left(\frac{ik[1-(l/f_t)]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_1^2}\right)}\right]$$
$$\times L_p^m\left[\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{\frac{2l^2}{\omega_1^2} - 2\omega_1^2 l^2\left(\frac{ik[1-(l/f_t)]}{2l} + \frac{C_{2n}}{a_1^2}\right)^2}\right] \quad (15)$$

Equation (15) represents the optical output field distribution in a misaligned FSOIs systems of a uniform circular aperture profile. Both the aperture size and the transverse misalignment of the microlens are considered in the equation. In subsection 2.5, we use the equation to estimate the crosstalk taking into account the effect of the uniform finite aperture of the microlens.

2.4. FSOIs with Gaussian circular aperture

Herein, we assume the utilization of microlens with circular aperture and Gaussian transmittance. Let $H(\rho_1)$ be the circular Gaussian aperture function with a_1 radius.

$$H(\rho_1) = A(\rho_1)G(\rho_1) = \begin{cases} G(\rho_1) & \rho_1 \le a_1 \\ 0 & \rho_1 > a_1 \end{cases} \quad (16)$$

where $G(\rho_1) = \exp\left(\frac{-\rho_1^2}{w_a^2}\right)$ and w_a^2 is the Gaussian aperture's width. Again, by expanding $A(\rho_1)$, $H(\rho_1)$ can be written as (17):

$$H(\rho_1) = \sum_{n=1}^{N} C_{1n}\exp\left(-\left[\frac{C_{2n}}{a_1^2} + \frac{1}{w_a^2}\right]\rho_1^2\right) \quad (17)$$

Substituting (17) into (7) and performing the integral, we obtain:

$$E_{2g}(\rho_2,\theta_2) = \left(\frac{ik}{2l}\right)^{m+1} \exp[-im\theta_2]\exp\left[\frac{ik}{2l}(d\rho_2^2 + g\rho_2 \cos\theta_2 + h\rho_2 \sin\theta)\right]$$
$$\times \left[\frac{\sqrt{2}}{\omega_1}\sqrt{(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2 \sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2}\right]^m$$
$$\times \sum_{n=1}^{N} C_{1n}\left[\frac{ik\left[1-\left(\frac{l}{f_t}\right)\right]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_a^2} + \frac{1}{\omega_1^2}\right]^{-m-p-1} \times \left[\frac{ik\left[1-\left(\frac{l}{f_t}\right)\right]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_a^2} - \frac{1}{\omega_1^2}\right]^p$$
$$\times \exp\left[-\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{4l^2\left(\frac{ik\left[1-\left(\frac{l}{f_t}\right)\right]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_a^2} + \frac{1}{\omega_1^2}\right)}\right]$$
$$\times L_p^m\left[\frac{k^2\left[(\rho_2\cos\theta_2 - 2s_x/\mathrm{f}_t)^2 + \left(\rho_2\sin\theta_2 - 2s_y/\mathrm{f}_t\right)^2\right]}{\frac{2l^2}{\omega_1^2} - 2\omega_1^2 l^2\left(\frac{ik[1-(l/f_t)]}{2l} + \frac{C_{2n}}{a_1^2} + \frac{1}{\omega_a^2}\right)^2}\right] \quad (18)$$

In (18) represents a closed form relation for the output fields in the misaligned FSOIs systems of circular Gaussian aperture. It includes the aperture size and the misalignment of the lens at the same time. Moreover, the dependence of the output filed on the misalignment parameters is obvious in the above equation. In the following subsection, we use the equation to estimate the crosstalk taking into account the effect of circular Gaussian aperture of the microlenses.

2.5. Crosstalk calculation

To study the effect of using tapered aperture on the misalignment tolerance we need to evaluate the crosstalk. For the sake of estimating the crosstalk, we refer back to Figure 2. Let the channel with the blue detector as the active channel. In this paper, two sources of crosstalk are taken into account. The first source is the stray light which is the mount of light from the active VCSEL that reaches to other detectors through neighboring micro lenses. Based on this, the stray crosstalk can be found using the following equations for the different apertures

$$P_{c1u} = P_{c11u} + P_{c12u} = 4 \iint_{\Omega_1} |E_1(\rho_1, \theta_1)|^2 \rho_1 d\rho_1 d\theta_1 + 4 \iint_{\Omega_2} |E_1(\rho_1, \theta_1)|^2 \rho_1 d\rho_1 d\theta_1 \quad (19)$$

$$P_{c1a} = P_{c11a} + P_{c12a} = 4 \iint_{\Omega_1} |E_1(\rho_1, \theta_1) A(\rho_1)|^2 \rho_1 d\rho_1 d\theta_1 + 4 \iint_{\Omega_2} |E_1(\rho_1, \theta_1) A(\rho_1)|^2 \rho_1 d\rho_1 d\theta_1 \quad (20)$$

$$P_{c1g} = P_{c11g} + P_{c12g} = 4 \iint_{\Omega_1} |E_1(\rho_1, \theta_1) H(\rho_1)|^2 \rho_1 d\rho_1 d\theta_1 + 4 \iint_{\Omega_2} |E_1(\rho_1, \theta_1) H(\rho_1)|^2 \rho_1 d\rho_1 d\theta_1 \quad (21)$$

where the subscripts u, a, and g are used to denote for no aperture, uniform hard aperture, and Gaussian aperture, respectively. In (19), (20), and (21) P_{c11} and P_{c12} are the crosstalk noises at the eight neighbor detectors. Ω is the detector' area. Diffraction induced crosstalk represents the second source of crosstalk which arises due to light diffraction from other VCSELs through other micro lenses to the active detector. In this case crosstalk can be obtained from the following (22):

$$P_{c2i} = P_{c21i} + P_{c22i} = 4 \iint_{\Omega_3} |E_{2i}(\rho_2, \theta_2)|^2 \rho_2 d\rho_2 d\theta_2 + 4 \iint_{\Omega_4} |E_{2i}(\rho_2, \theta_2)|^2 \rho_2 d\rho_2 d\theta_2 \quad (22)$$

The subscript i should be replaced by u, a, or g to find the crosstalk for no aperture, uniform aperture, or Gaussian aperture case, respectively. Useful signal power can be defined as the power received by the active detector through its active channel and is given as (23):

$$P_{si} = \iint_{\Omega} |E_{2i}(\rho_2, \theta_2)|^2 \rho_2 d\rho_2 d\theta_2 \quad (23)$$

Using (19) to (23), the signal-to-crosstalk (SCR) ratio can be calculated as (24).

$$SCR_i = \frac{P_{si}}{P_{c1i} + P_{c2i}} \quad (24)$$

3. RESULTS AND DISCUSSION

To show the impact of using lenses with tapered aperture on the crosstalk of a misaligned system we refer to Figure 2 and assume the following parameters: wavelength (λ) of 0.850 µm, LG beam's waist radius (w_o) for the VCSEL of 3 µm, micro lenses focal length (f_t) of 720 µm, and micro lenses diameter of 250 µm. The interconnection distance and the radius of the hard aperture are considered to be 2.5 mm and 125 µm, respectively. In addition, the width of the Gaussian aperture is assumed to be 125 µm. In Figure 3, we showed the SCR as a function of the detector size for the aligned FSOIs model for both uniform and Gaussian apertures. Using uniform aperture, the maximum SCR is 25 and it is 93 using the Gaussian aperture. Moreover, the optimum detector size for the Gaussian aperture (14 µm) is less than that of the uniform hard-edge aperture (23 µm). The presence of such optimum is due to the fact that the diffraction induced crosstalk is mainly determined by the detector size and the stray crosstalk is determined by the microlens size. For a given microlens size, the stray crosstalk is fixed and is larger than the diffraction crosstalk at small detector size. Given this, the decrease of the SCR with small detector size is because of the reduction in the signal power. For large detector size, the diffraction crosstalk is larger and increases with the detector size.

Figure 4 demonstrates the SCR as a function of the detector radius with a misalignment of 10 µm for the micro lens in the x-direction. It is clear from the figure that the SCR decreases significantly with misalignment. The optimum level of SCR is decreased to 18.5 using Gaussian aperture and to 7.5 using uniform aperture. In addition, the optimum size of the detector decreases with increasing the misalignment to tolerate the decrease in the SCR. Optimum detector radii when using uniform and Gaussian apertures are 18 µm, and 12 µm, respectively. Figure 5 shows the SCR versus transverse misalignment for a fixed detector size. The figure clearly demonstrates that the SCR decreases when the misalignment increases. If we set the minimum acceptable SCR to 10 for proper transmission, the optical system can tolerate misalignment up to 14 µm for the case of Gaussian aperture and up to 6 µm for the uniform hard aperture case.

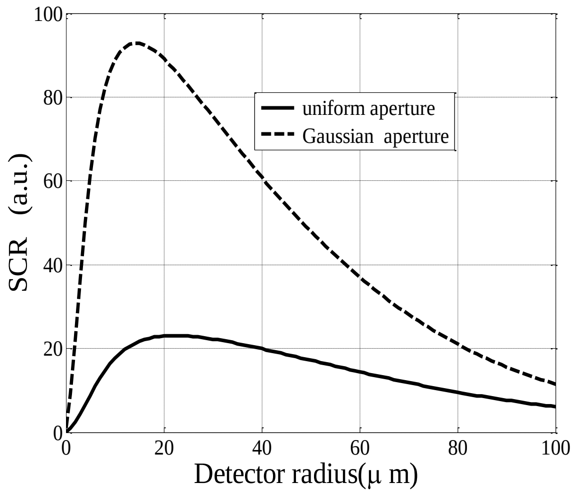


Figure 3. SCR as a function of detector size for aligned FSOIs systems using uniform and Gaussian apertures

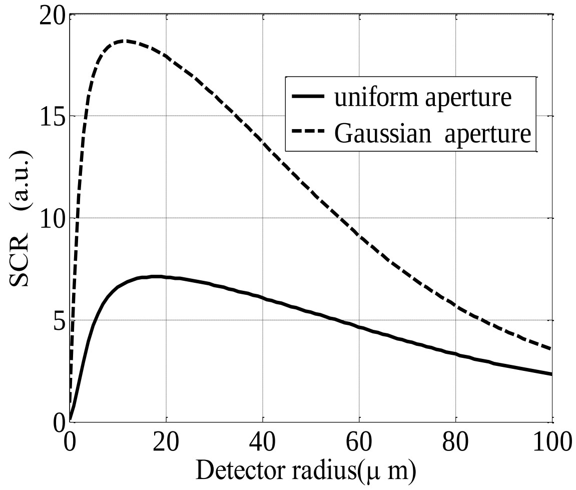


Figure 4. SCR as a function of detector radius for misaligned FSOIs system using uniform and Gaussian apertures. Misalignment is 10 µm

The increase in the system tolerance can be explained by the aid of using Figures 6 and 7. Figure 6 shows the normalized crosstalk versus transverse misalignment. As we can see the crosstalk when using the Gaussian aperture is less than that of the uniform hard aperture for all misalignment values. Even though the normalized signal power is less when using the Gaussian aperture as shown in Figure 7 but the reduction of the crosstalk results in more SCR as expected.

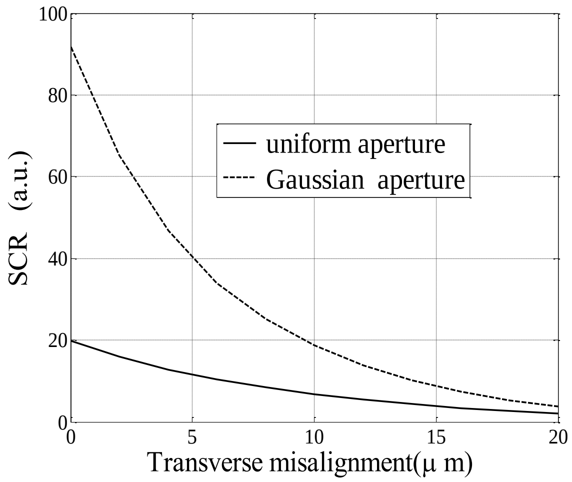


Figure 5. SCR versus transverse misalignment for misaligned FSOIs system using uniform and Gaussian apertures. Detector radius is 12 µm

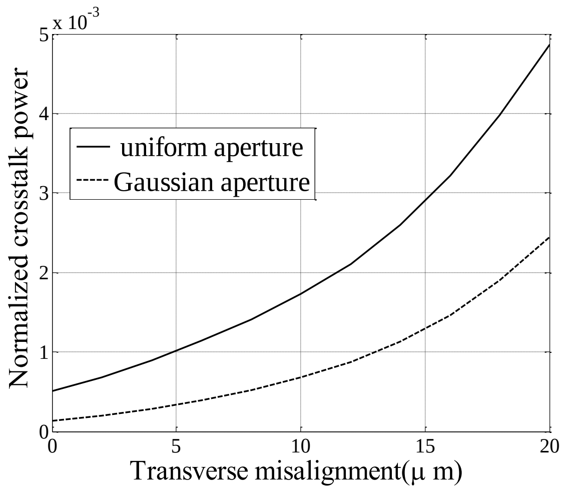


Figure 6. Normalized crosstalk versus transverse misalignment for misaligned FSOIs system using uniform and Gaussian apertures. Detector radius 12 µm

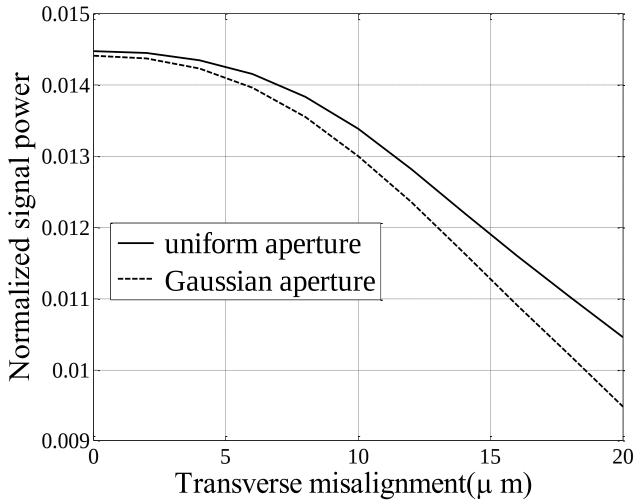


Figure 7. Normalized signal power as a function of transverse misalignment for misaligned FSOIs system using uniform and Gaussian apertures. Detector radius 12 μm

4. CONCLUSION

A misaligned first order free space optical interconnects system employing micro lenses with tapered aperture has been analyzed. The output optical field has been evaluated using the generalized diffraction integral formula assuming Gaussian profile for the micro lens transmittance. Based on the obtained output field, the signal-to-crosstalk ratio has been evaluated. The numerical results have shown that the tolerance to misalignment could be increased and the reduction of the signal-to-crosstalk ratio caused by the misalignment could be kept within the useful ranges at higher misalignment by using micro lenses with tapered transmittance profile.

REFERENCES

[1] A. Liu, P. Wolf, J. A. Lott, and D. Bimberg, "Vertical-cavity surface-emitting lasers for data communication and sensing," *Photonics Research*, vol. 7, no. 2, pp. 121–136, Jan. 2019, doi: 10.1364/prj.7.000121.

[2] K. Wang, C. Lim, E. Wong, K. Alameh, S. Kandeepan, and E. Skafidas, "High-speed reconfigurable free-space optical interconnects with carrierless-amplitude-phase modulation and space-time-block code," *Journal of Lightwave Technology*, vol. 37, no. 2, pp. 627–633, Jan. 2019, doi: 10.1109/JLT.2018.2881728.

[3] M. Kaba *et al.*, "Free space optical interconnect (FSOI) modules for short range data transfer applied to board to board high rate communication," in *Advanced Free-Space Optical Communication Techniques and Applications III*, Oct. 2017, doi: 10.1117/12.2277916.

[4] S. Fuada, T. Adiono, A. P. Putra, and Y. Aska, "Noise analysis in VLC optical link based discrette OP-AMP trans-impedance amplifier (TIA)," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 15, no. 3, pp. 1012–1021, Sep. 2017, doi: 10.12928/telkomnika.v15i3.5737.

[5] X. Zhao, L. Zhu, S. Fu, C. Liu, M. Tang, and D. Liu, "Dual-band accelerating beams enabled full duplex free-space optical interconnection," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 27, no. 1, pp. 1–7, Jan. 2021, doi: 10.1109/JSTQE.2020.2991756.

[6] M. H. Ali, R. I. Ajel, and S. Abdul-kader Hussain, "Performance analysis of beam divergence propagation through rainwater and snow pack in free space optical communication," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 10, no. 3, pp. 1395–1404, Jun. 2021, doi: 10.11591/eei.v10i3.2857.

[7] H. P. Kuo *et al.*, "Free-space optical links for board-to-board interconnects," *Applied Physics A*, vol. 95, no. 4, pp. 955–965, Jun. 2009, doi: 10.1007/s00339-009-5144-z.

[8] B. Ciftcioglu *et al.*, "3-D integrated heterogeneous intra-chip free-space optical interconnect," *Optics Express*, vol. 20, no. 4, Feb. 2012, doi: 10.1364/OE.20.004331.

[9] J. A. Kash *et al.*, "Optical interconnects in exascale supercomputers," in *2010 23rd Annual Meeting of the IEEE Photonics Society, PHOTINICS 2010*, Nov. 2010, pp. 483–484, doi: 10.1109/PHOTONICS.2010.5698971.

[10] M. R. T. Tan, D. A. Fattal, and T. Morris, "Misalignment tolerant free space optical transceiver." U.S. Patent No. 8,315,526, 2012.

[11] M. H. Ayliffe and D. V Plant, "On the design of misalignment-tolerant free-space optical interconnects," in *Proceedings of SPIE - The International Society for Optical Engineering*, 2000, vol. 4089.

[12] H. A. Duong, V. L. Nguyen, and K. T. Luong, "Misalignment fading effects on the ACC performance of relay-assisted MIMO/FSO systems over atmospheric turbulence channels," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 1, pp. 966–973, Feb. 2022, doi: 10.11591/ijece.v12i1.pp966-973.

[13] N. Al-ababneh, "Misalignment tolerance in free space optical interconnects," *6 th International Conference on Computational and Eperimental Science and Engineering (ICCESEN-2019)*, pp. 241–247.

[14] A. Mansour, R. Mesleh, and M. Abaza, "New challenges in wireless and free space optical communications," *Optics and Lasers in Engineering*, vol. 89, pp. 95–108, Feb. 2017, doi: 10.1016/j.optlaseng.2016.03.027.

[15] H. Aldiabat and N. Al-ababneh, “Bandwidth density optimization of misaligned optical interconnects,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1626–1635, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1626-1635.
[16] F. Lacroix, M. Châteauneuf, X. Xue, and A. G. Kirk, “Experimental and numerical analyses of misalignment tolerances in free-space optical interconnects,” *Applied Optics*, vol. 39, no. 5, Feb. 2000, doi: 10.1364/AO.39.000704.
[17] N. S. F. Ozkan, W. L. Hendrick, P. J. Marchand, and S. C. Esener, “Misalignment tolerance analysis of free-space optical interconnects via statistical methods,” *Applied Optics*, vol. 41, no. 14, May 2002, doi: 10.1364/AO.41.002686.
[18] F.-C. F. Tsai, C. J. O’Brien, N. S. Petrović, and A. D. Rakić, “Analysis of optical channel cross talk for free-space optical interconnects in the presence of higher-order transverse modes,” *Applied Optics*, vol. 44, no. 30, Oct. 2005, doi: 10.1364/AO.44.006380.
[19] F.-C. F. Tsai, C. J. O’Brien, N. S. Petrovic, and A. D. Rakic, “The effect of the higher order modes on the optical crosstalk in free-space optical interconnect,” in *Conference on Optoelectronic and Microelectronic Materials and Devices, 2004.*, 2005, pp. 319–322, doi: 10.1109/COMMAD.2004.1577555.
[20] N. S. Petrović and A. D. Rakić, “Modeling diffraction in free-space optical interconnects by the mode expansion method,” *Applied Optics*, vol. 42, no. 26, Sep. 2003, doi: 10.1364/ao.42.005308.
[21] W. Hu, X. Li, J. Yang, and D. Kong, “Crosstalk analysis of aligned and misaligned free-space optical interconnect systems,” *Journal of the Optical Society of America A*, vol. 27, no. 2, pp. 200–205, Jan. 2010, doi: 10.1364/josaa.27.000200.
[22] N. Al-Ababneh, “Crosstalk in misaligned free space optical interconnects: Modelling and simulation,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 3, pp. 1620–1629, Jun. 2019, doi: 10.11591/ijece.v9i3.pp1620-1629.
[23] N. Al-ababneh, “Aberrated microlenses to reduce crosstalk in free space optical interconnects systems,” *Modern Applied Science*, vol. 12, no. 5, Apr. 2018, doi: 10.5539/mas.v12n5p100.
[24] Y. Cai and S. He, “Propagation of a Laguerre–Gaussian beam through a slightly misaligned paraxial optical system,” *Applied Physics B*, vol. 84, no. 3, pp. 493–500, Sep. 2006, doi: 10.1007/s00340-006-2321-z.
[25] N. Bonneux and A. B. J. Kuijlaars, “Exceptional Laguerre Polynomials,” *Studies in Applied Mathematics*, vol. 141, no. 4, pp. 547–595, Jan. 2018, doi: 10.1111/sapm.12204.
[26] T. Yu, H. Xia, W. Xie, G. Xiao, and H. Li, “The generation and verification of Bessel-Gaussian beam based on coherent beam combining,” *Results in Physics*, vol. 16, Mar. 2020, doi: 10.1016/j.rinp.2019.102872.

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