Board-to-board optical interconnects using a parabolic mirror for high angular misalignment tolerance

M. Gross, D. Song, and S. Esener
UC San Diego, Dept. of ECE, 9500 Gilman Dr., La Jolla, CA 92093-0407
Tel.: (858) 534 6226, FAX: (858) 534 1225, email: mgross@ece.ucsd.edu

Abstract: A free space optical board-to-board interconnect is presented, utilizing a parabolic mirror to achieve high angular tolerance. A relation between the input and output angle of the system is calculated and simulation results are given.

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1. Introduction

Optical interconnects are soon to appear in the box, replacing electrical traces [1-3]. This development is caused by two phenomena: First, higher speed increases the attenuation in electrical interconnects, reducing the maximum interconnect distance with increasing bit rate per line. The attenuation of optical interconnects is bit rate independent, so that for a certain distance optical interconnects offer the better solution above a threshold bit rate. The second issue is crosstalk, which is increasing for electrical interconnects with higher channel density. Optical interconnects on the other hand do not suffer from this problem, with the channel density limited only by the transmitter and receiver optoelectronics, when using free space optical interconnects (FSOI).

One task, which will be treated in this paper, is the connection of a transmitter on a removable computer board with a receiver located on a backplane. The receiver can be either a photodiode or the end of a fiber, which then transports the signal to more distant destinations. When introducing free space optics we have the challenge of overcoming misalignments originating from the movements of the board, especially the angular misalignment depicted in fig. 1, which has the biggest influence when the computer board is fixed in a slot in the backplane.

Fig. 1. Principle of a board-to-board optical interconnect with a parabolic mirror to enhance the angular misalignment tolerance

This board-to-board optical interconnect includes a mirror, which is the central part of the interconnect, giving the system a high tolerance to angular misalignments the way shown in fig. 1. The mirror is parabolic shaped and the incoming light beam is pointing to the focal point of the parabola. Therefore, all light beams coming from different angles are reflected into beams parallel to the backplane. When a lens is then used as depicted with the receiver in the focal point all incoming light beams are hitting the receiver regardless of the angle between board and backplane, provided the incoming beam hits the mirror and the output lens. With this setup an efficient board-to-board/fiber interconnect can be built.

Since a fiber has a limited acceptance angle it is important to know how the misalignment angle translates into the fiber input angle, which will be calculated in the following theoretical section. After this, simulation results will be presented, showing the alignment tolerances of an example system.
2. Theory

The setup is shown in fig. 2 with all the definitions needed to calculate the relation between the misalignment angle \( \theta_1 \) and the fiber input angle \( \theta_2 \). The parabola defining the mirror has the function \( p(y) = \frac{-1}{2p} y^2 \), the point \( P_1 \) is the focal point of the parabola, the aiming point of the incoming light beams.

\[
p : x = -\frac{1}{2p} y^2
\]

Fig. 2. Mathematical definitions for the interconnect setup for calculation of the relation between the misalignment angle \( \theta_1 \) and the fiber input angle \( \theta_2 \).

The relationship \( y_2 = p/(2 \tan \theta_1) \) can be deduced from fig. 2. Calculation of the straight line \( g \), which represents the misaligned incoming light beam, using the points \( P_1 (-p/2, 0) \) and \( P_2 (0, y_2) \) gives

\[
g(y) = (\tan \theta_1) y - \frac{p}{2}
\]

(1)

The intersections of the parabola \( p \) and the straight line \( g \) are

\[
y_{1/2} = -p \tan \theta_1 \pm p \sqrt{\tan^2 \theta_1 + 1}
\]

(2)

Interesting for this case is the upper intersection \( y_1 \), where the two terms are added. Since the original beam \( (\theta_1 = 0) \) is at \( y_0 = p \) after the reflection, we can now calculate the y-shift of the skewed beam as \( \Delta y = y_0 - y_1 \):

\[
\Delta y = p \left(1 + \tan \theta_1 - \sqrt{\tan^2 \theta_1 + 1}\right)
\]

(3)

Assuming that the original beam is on the optical axis of the output lens, which has the focal length \( f \) (no aberration taken into account here), the lateral shift \( \Delta y \) translates into the output angle \( \theta_2 \) according to the relation \( \tan \theta_2 = \Delta y/f \). Together we get the exact result for the relation between the angles \( \theta_1 \) and \( \theta_2 \):

\[
\tan \theta_2 = \frac{p}{f} \left(1 + \tan \theta_1 - \sqrt{\tan^2 \theta_1 + 1}\right)
\]

(4)

For the optical interconnects we expect angular misalignments of not more than a few degrees. For these small angles we can write \( \tan \theta = \theta + O(\theta^2) \) and \( \sqrt{\theta^2 - 1} = 1 + O(\theta^2) \). Then the relation reduces to:

\[
\theta_2 = \frac{p}{f} \theta_1 \quad \text{valid for small angles } \theta_1/2
\]

(5)

The input and output angles of a light beam are related through the size of the parabolic mirror and the focal length of the output lens. Since these parameters are unrelated it is possible to design a system for a given fiber and maximum displacement angle. This system is not sensitive to small vertical displacements of the input board since this causes no movement of the input beam. A lateral shift in the board plane is also irrelevant as long as the beam hits the output lens. Since all other movements and rotations are restricted by the slot which holds the board, this system helps to build a highly reliable, robust optical interconnect.

3. Simulations

In the following we present simulation results of an example system to show the positive influence of the parabolic mirror, which is designed to meet this system restrictions: The maximum misalignment angle is assumed to be \( \theta_1 = \ldots \)
5 deg, the maximum fiber input angle $\theta_2 = 10$ deg. Together with a focal length of $f = 1$ mm of the output lens eq. 5 gives $p = 2$ mm for the parameter of the parabola. The system was simulated with CodeV® (ORA), results are shown in fig. 3. The parabolic mirror (100% reflectivity) and the output lens (BK7 glass, spherical lens) are modeled with the parameters given above, the input beam is collimated with a microlens (BK7 glass, diameter: 0.25 mm, focal length: 0.63 mm).

As can be seen in fig. 3b) all rays of the light beam are hitting the fiber (assumed target area with 100 $\mu$m diameter) at the design maximum misalignment angle of 5 deg. Table 1 shows the results of a further misalignment tolerance analysis. These are tolerances for 3 dB power roll-off for all relevant lateral and angular misalignments of the system ($\gamma$-misalignment and $\beta$-tilt –tilt around y-axis– have no influence in this simulation).

Table 1. 3 dB power roll-off tolerances (for axis assignment see fig. 2; $\theta$: tilt around z-axis; $\gamma$: tilt around x-axis)

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>$\Delta \xi$ ($\mu$m)</th>
<th>$\Delta \zeta$ ($\mu$m)</th>
<th>$\Delta \theta$ (deg)</th>
<th>$\Delta \gamma$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/- 100</td>
<td>+/- 300</td>
<td>+/- 9</td>
<td>+/- 3</td>
<td></td>
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The tolerance for the $\theta$-tilt is very high compared to that of the $\gamma$-tilt as expected by the design of the system. The lateral tolerances are high enough to be met by modern fabrication technologies.

4. Conclusions

In this paper a free space optical board-to-backplane interconnect was presented. Central element is a parabolic shaped mirror, which gives the system a high angular tolerance for in-plane rotation, when applied together with an output lens. The relation between the input and output angle was calculated with the result that this is dependent on both the parabolic mirror size and the output lens focal length. Since these are unrelated, optimization for a vast parameter range is possible. Ray-tracing simulations of an example system were conducted, showing a high angular tolerance as expected.

So far only one channel was taken into account, but the system can easily be extended into lateral direction to a multi-channel device with a VCSEL array as input and a fiber ribbon as output. This will be investigated in the future.

5. References