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Research Article

Characterization of a Reconfigurable Free-Space Optical Channel for Embedded Computer Applications with Experimental Validation Using Rapid Prototyping Technology

Rafael Gil-Otero,[1] Theodore Lim,[2] and John F. Snowdon[1]

[1] *Optical Interconnected Computing Group (OIC), School of Engineering and Physical Science, Heriot-Watt University, Edinburgh EH14 4AS, UK*
[2] *Digital Tools Manufacturing Group (DTMG), School of Engineering and Physical Science, Heriot-Watt University, Edinburgh EH14 4AS, UK*

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Free-space optical interconnects (FSOIs) are widely seen as a potential solution to current and future bandwidth bottlenecks for parallel processors. In this paper, an FSOI system called optical highway (OH) is proposed. The OH uses polarizing beam splitter-liquid crystal plate (PBS/LC) assemblies to perform reconfigurable beam combination functions. The properties of the OH make it suitable for embedding complex network topologies such as completed connected mesh or hypercube. This paper proposes the use of rapid prototyping technology for implementing an optomechanical system suitable for studying the reconfigurable characteristics of a free-space optical channel. Additionally, it reports how the limited contrast ratio of the optical components can affect the attenuation of the optical signal and the crosstalk caused by misdirected signals. Different techniques are also proposed in order to increase the optical modulation amplitude (OMA) of the system.

1. INTRODUCTION

The world's information technology industry is moving a step closer towards incorporating photonics with the aim of overcoming bandwidth bottlenecks. The recent development of the first electrically driven hybrid silicon laser for Intel at University of Santa Barbara [1] is a good example of technological advancements towards standard high-volume, low-cost silicon manufacture techniques available for integrating silicon photonic chips.

For communication technology, fiber-based optical interconnects have already proven their advantage over electrical interconnects over long distances. However for multiparallel processor applications (massively parallel processors or "dual-core processors") where high bandwidth is required over short distances (mm-m), the utilization of fiber becomes difficult and costly.

Free-space optical interconnection networks are particularly attractive for connecting many nodes in a complex topology, where a node may be a board or a chip. Potential applications occur both in multiprocessor computing systems and switching systems. Several architectures exploiting this technology have been designed [2, 3]. These systems are generally based on an optical system, often referred to as an optical bus that comprises several image-relay stages in a linear (or ring) topology.

It should be noted that despite its linear structure, such optical "buses" could support arbitrary logical topologies [3, 4]. This is particularly important for high-dimensional networks that cannot be easily designed as a free-space system by a direct mapping of the logical topology into a 3D space.

One important choice in the implementation of an optical bus is the manner in which each logical network link is supported. Consider that in general, a link is between a pair of nodes that are not adjacent (physically) in the linear topology of the bus. One approach is to form such links from multiple hops between physically adjacent nodes. This has the advantage of simplifying the optical system design and assembly [5]. The disadvantage is that the entire bandwidth of the bus passes through the optoelectronic interface at each node. An alternative approach is to use a single hop to form each (physically) long-distance link, with the signal remaining in the optical domain throughout. Since a high-performance free-space optical system can carry more parallel signals than the optoelectronic interface, this method has the potential to fully exploit the capacity of the optical system. However, as the signal beams travel further through the optics, beam quality degenerates and aberration occurs, thus the channel bit rate must be lowered. In [6], these two approaches for implementing free-space optical interconnection networks were compared and it was found that the single-hop approach could provide a higher bandwidth per link. However this higher bandwidth varies depending on the type of networks and number of nodes connected. For the single-hop approach, the maximum number of nodes connected depends on the physical architecture of the network and the maximum number of stages that the optical signal can go through in the network before becoming too weak. Therefore, it is important to establish the maximum number of stages.

In this paper, an experimental demonstrator has been built based on an FSO interconnect called optical highway, (OH) [2, 7]. This demonstrator has been used to determine how parameters such as polarization losses, crosstalk caused by misdirected signal, power of the emitters, sensitivity of the detector, type of modulation code and bit error rate (BER) can influence the optical quality of the signal, in terms of optical modulation amplitude (OMA) and contrast ratio (r_e), and therefore in determining the maximum number of stages that the optical signal can go through in the system.

The paper is structured as follows. Section 2 explains the principle of operation of the OH and the modification introduced with regard to previous designs in order to increase the number of nodes connected. Section 3 reports the demonstrator built for this experiment using a novel technology called rapid prototyping (RP) that allows fast construction of low-cost mechanical structures. Section 4 presents and analyzes the results with eye diagram of an optical signal that is routed through the OH. Different techniques for increasing the optical quality and maximizing the number of stages that the optical signal can go through the OH for a certain BER are also proposed in Section 5. Finally, Section 6 concludes the paper.

2. OPTICAL HIGHWAY

OH is a polarized beam routing system which provides a very high spatial and temporal bandwidth to which a large number of nodes, in this case processors with associated memory, can be connected.

The OH is designed to be a flexible architecture onto which multiple interconnected topologies can be implemented dynamically by using active optical elements, such as liquid crystals (LCs). LCs are slow for switching packet but can be used to reconfigure topology for fault tolerance and algorithm reasons.

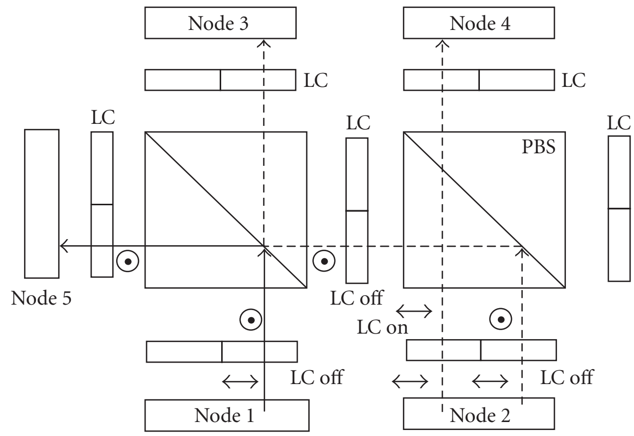


Figure 1: Example of an implementation of two stages of a free-space OH.

A number of designs for OHs have been suggested and built [2, 4, 5]. However in order to minimize the optical losses and reduce the number of different optical components, we are going to propose the structure shown in Figure 1 where only two different optical components are required, polarized beam splitter (PBS) and LC.

In this design, polarization is used to route signals through the system. The basic operation is that a linear polarized signal from a node will be routed to a twisted nematic LC, which can either rotate the polarized light by 90 degrees, if switched off, or leave the light unchanged if switched on. The signal then travels towards a PBS, which can route the signal in two different directions, transmitted or reflected, depending on how the LC has set the linear polarization of the signal.

This structure, assembly LC/PBS, constitutes what we call an optical stage of the OH. In Figure 1, two of these stages are represented.

The OH utilizes multiple imaging stages. Note that although a signal may pass through multiple optical stages to travel from the source to destination nodes, these optical stages are passive and do not involve any optoelectronic conversion of the signal. Therefore the latency associated to the routing can be reduced to the minimum, that is, conversion from electrical to optical in source node and optical to electrical in the destination node.

Figure 1 also shows some unique properties of FSO interconnected systems. For example, due to the noninteraction of light, the optical signal that communicates node 2 with node 4 can cross the optical signal that communicates node 2 with node 5. Another characteristic is that the same channel (PBS point) can be used for routing different signals at the same time. In Figure 1, we can see how node 1 and node 5 can communicate at the same time as node 2 and node 3 using the same PBS point. This characteristic is important in order to optimize the efficiency, that is, number of emitters and detectors working at the same time, of the system. These properties make OH suitable for embedding complex topologies such as a completed connected topology. In addition, the use of LCs as reconfigurable elements enables multiple topologies such as a mesh or hypercube to be embedded.

Since OH capability is based on routing the optical signal through multiple optical stages, losses caused by attenuation and crosstalk became a major problem. As mentioned, the objective of this paper is to analyze how the optical signal is affected by crosstalk and attenuation on the OH and how the optical quality can be increased in order to increase the maximum number of optical stages that the optical signal can go through in the system.

3. EXPERIMENTAL SETUP

In order to analyze the optical quality of a signal that travels through the OH, a three-stage (PBS/LC) optical system has been designed. Figure 2 shows the scheme of the optical system proposed, where a polarized optical signal is routed through the OH. Then, selecting the appropriate LCs, the optical signal can be routed to any of the three outputs.

Figure 2 shows also effect of Fresnel reflection at the optical surfaces of the PBSs resulting in misdirected signals being routed to the wrong output causing a source of noise. In [4, 8], it is suggested that rather than aberration, the fact that the misdirected signal accidentally routes from a node to the nearest neighbor is the main factor which limits the size of the network. For this reason, we proposed an experiment where the problem of the misdirected signal is isolated and studied independently from other sources such as aberration and crosstalk caused by misalignment and high spatial bandwidth (number of physical layers). Only one optical channel will be routed through the system and eye diagrams of the optical signal and the misdirected signal will be analyzed at each output.

A mechanical structure has been built for this particular experiment to hold four different optical components, transmissive twisted nematic liquid crystals from Excel Display LC Company [9], wired grid plates from Motex [10] working as polarizing beam splitter, an AlGaInP laser diode 3 mW CW used as a source with its collimator and polarizers.

The mechanical structure has been built using a novel technique called rapid prototyping (RP). The use of RP as a fast and low-cost technique for testing experimentally FSOI systems has already been used successfully in [4]. In this experiment, a bench of 150 mm × 40 mm × 45 mm has been built with an RP machine in just one hour. Figure 3 shows the bench with different slots to insert the different optical components.

In order to obtain an eye diagram of a free-space optical signal, A tektronix programmable stimulus system HFS9009 was used for generating the data signals, on-off-key (OOK) code 50 Kb/s nonreturn-to-zero (NRZ) data stream with < 20 picoseconds rise and fall times. The amplitude of the digital signal was 400 mV and the offset was 2.5 V.

For recovering the optical signal at each output of the system, a 10 MHz bandwidth amplified silicon detector of 3.5 mm × 3.5 mm of area has been used.

The eye diagrams of the signal are analyzed by the infimun agilent 6 GHz real-Time scope.

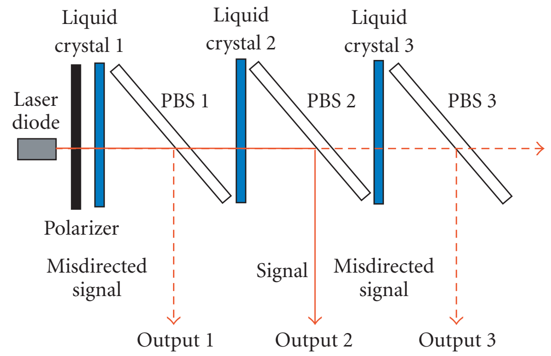


Figure 2: Experimental design of a three-stage optical system.

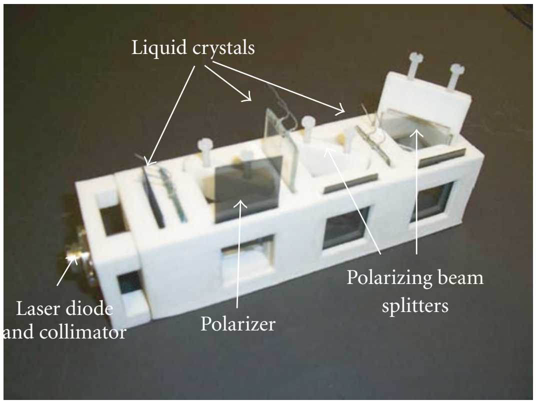
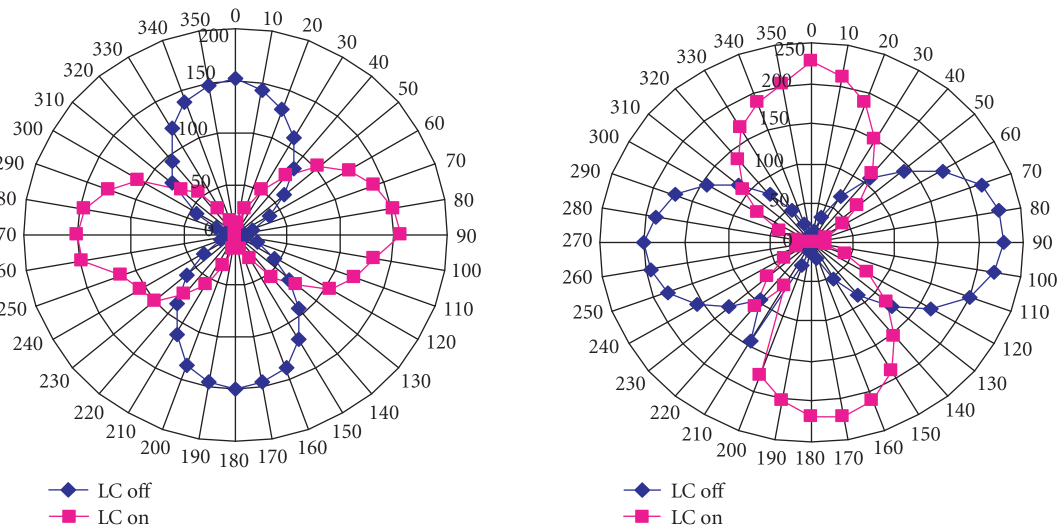


Figure 3: Optomechanical structure built using rapid prototyping techniques.

In order to achieve the most satisfactory result in the experiment, it was necessary to characterize and optimize the TNLC used. Three parameters have been defined, the contrast ratio of the LC at each state, ε_0 (LC on) and ε_1 (LC off), and the attenuation of the LC, α. The contrast ratio ε_0, measures how good the LC twists by 90 the polarized light. This is achieved by measuring the intensity detected after a polarizer, Po, has been placed at the output of the system and oriented parallel or perpendicular to the input polarizer, Pi. When the LC is off, the polarized light is supposed to twist by 90 degrees. Therefore the intensity detected when Pi and Po are perpendicular has to be as high as possible and when they are parallel, it has to be as low as possible. The parameter ε_1 measures how good the LC keeps the polarized light untwisted. In this case, the maximum power is detected when both polarizers, Pi and Po, are parallel and the minimum, when they are perpendicular to each other:

$$\varepsilon_0 = 10\log\left(\frac{I_{\mathrm{Po}\perp\mathrm{Pi}}}{I_{\mathrm{Po}//\mathrm{Pi}}}\right)_{\mathrm{LC\ on}}, \qquad \varepsilon_1 = 10\log\left(\frac{I_{\mathrm{Po}//\mathrm{Pi}}}{I_{\mathrm{Po}\perp\mathrm{Pi}}}\right)_{\mathrm{LC\ off}}. \tag{1}$$

From (1), we can see that the lower the values of ε_0 and ε_1 are (in dB), the better the LCs work.



(a) (b)

Figure 4: Characterization of p-polarized and s-polarized light when the LC is off and on; polarization characteristic when initial polarization is (a) horizontal and (b) vertical.

After optimizing the TNLC under different voltages and rotational and translational positions, we see that the best values for the contrast ratios ε_0 and ε_1 and the attenuation are −19 dB, −19 dB, and −0.7 dB, respectively.

Figure 4 shows how a linear polarized beam is affected by the LC. Using an analyzer at the output of the LC, we can obtain the polarization characteristics of the beam once it has gone through the LC.

It can be observed that after optimization, either for a vertical, p, or horizontal, s, polarized light used as initial input, the LC keeps the linearity of the polarized light in both states of the LC, that is, on and off. Secondly, it can be observed that by switching the LC from on to off or from off to on, the polarized light is twisted by 90 degrees, which is the result that we were looking for in order to use an efficient polarized beam router system.

4. RESULTS

This section studies the attenuation of the optical signal and the crosstalk at each output caused by misdirected signals.

In order to analyze the optical signals, two different eye diagrams at each output have been obtained; one when the signal is directed to this output and the other when the signal is directed to any other output but a misdirected signal is routed into the output under testing.

Figure 5 shows the eye diagrams at the three outputs of the system. The on and off states of the LC are represented by the scalars 1 and 0, respectively. In this demonstrator, three LCs have been used, therefore a vector of three elements determines their states. The vector [0, 0, 0] means that all the LCs are off and the signal is routed to the first output R1. When the LCs are selected [1, 0, 0] and [1, 1, 0], the optical signal is routed to the outputs R2 and R3, respectively.

Table 1: Eye diagram parameters when no cleanup polarizers are used. These are the values obtained at each output when the optical signal is directed to each output.

Parameters	Output 1	Output 2	Output 3
Eye height (mV)	1655	1146	751
Eye width (us)	20	20	20
Q-factor	62.07	44.09	35.74
Jitter RMS (ns)	0	0	0

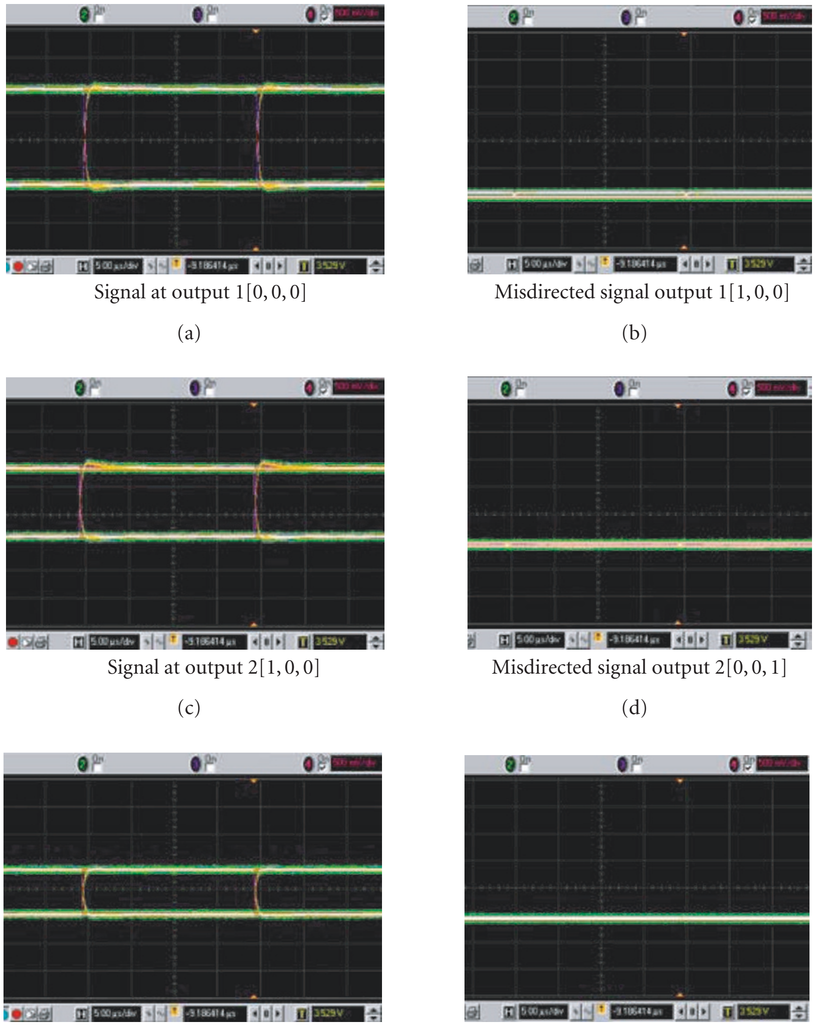
Table 1 summarizes the eye diagram parameters obtained when the optical signal is routed into each output. As can be seen from the table, the eye height decreases by 1.4 dB per stage. As a result, the quality factor Q also decreases. However, after three stages, the value of Q is still far from the value of 6, which is the minimum necessary to achieve a BER of 10^{-9} [11].

On the other hand, the signal level after three stages is high enough not to degenerate the eye width and the jitter RMS parameters.

As we can see in Figure 5, no eye diagram and therefore no eye parameters can be obtained for the misdirected signals at each output. This means that the misdirected signals detected are too weak when compared with the desired signal that was routed to that output.

As a consequence of these results, the misdirected signals at each output can be considered as a CW value when it is compared with the directed signal detected where two clear values, the logic 0 and logic 1, can be distinguished.

Secondly, the value of the misdirected signal at each output is inferior to the value, at each output, of the logic 0 of the directed signal.



Signal at output 1[0, 0, 0]

(a)

Misdirected signal output 1[1, 0, 0]

(b)

Signal at output 2[1, 0, 0]

(c)

Misdirected signal output 2[0, 0, 1]

(d)

Signal at output 3[0, 0, 1]

(e)

Misdirected signal output 3[0, 0, 0]

(f)

FIGURE 5: Diagrams at the three outputs in the 3-stage optomechanical system.

These conclusions prove that as a result of the optimization of each component, the system worked as required. A more detailed analysis has been done in order to compare the value of the misdirected signal at any output with the value of the digital "0" at any output. It also has been analyzed how the optical signal is affected in terms of polarization losses and attenuation when the signal goes through the optical stages.

Figure 6 shows the optical power value of the logic 1, $P1$, logic 0, $P0$, and the crosstalk, $P_{\text{crosstalk}}$, at each output. As can be seen, $P_{\text{crosstalk}}$ at each output is lower than $P0$ at the same output. In fact, the extinction ratio of the optical signal defined as $r_e = P1/P0 = 8.8$ at the first output is lower than the extinction ratio of the misdirected signal defined as $r_{\text{crosstalk}} = P1/P_{\text{crosstalk}} = 12.7$ at the first output. From Figure 6, we can see that the optical quality of the signals in the three-stage system is determined by optical modulation amplitude of the system, defined as $\text{OMA}_{\text{system}} = P1_{\min} - P0_{\max}$, where $P1_{\min}$ is the value of $P1$ at the third output and $P0_{\max}$ is the value of $P0$ at first output.

We can conclude that in spite of using off-the-shelf LCs after a correct optimization and without the need of precise systems of alignment, the limiting factor in the optical budget of the OH system is not crosstalk, but $P0$.

Since $r_e < r_{\text{crosstalk}}$, the bit error rate (BER) of the optical signal can be analyzed without the need of having to take into account the influence of crosstalk. BER is determined entirely by the optical signal-to-noise ratio, which is commonly called the Q-factor:

$$Q = \frac{\text{OMA}}{\sigma_1 + \sigma_0}\left(\frac{r_e - 1}{r_e + 1}\right). \tag{2}$$

The Q-factor is defined as the optical modulation amplitude $\text{OMA} = P1 - P0$ divided by the sum of the rms noise on the high and low optical levels. The term $(1 - r_e)/(1 + r_e)$, known as power penalty, is due to the difference between $P0$

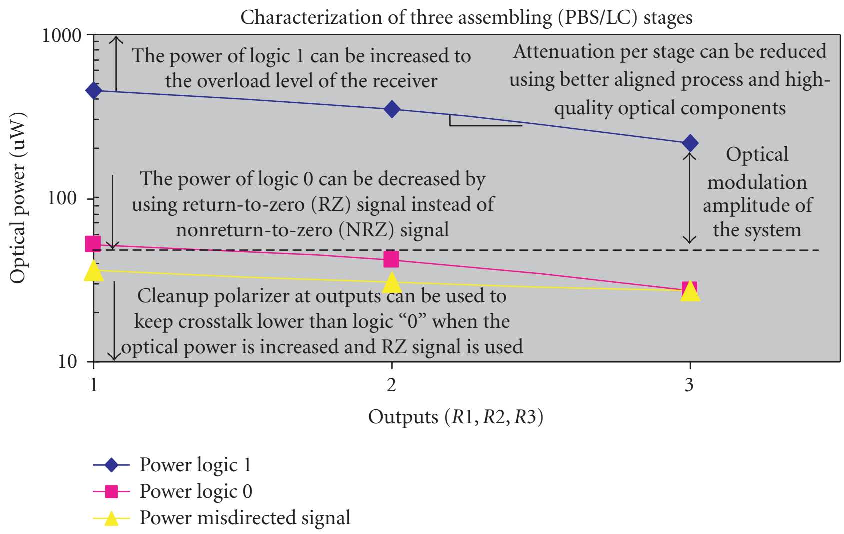


FIGURE 6: Values in mV of the logic "1," logic "0," and the crosstalk.

TABLE 2: Techniques used for increasing the optical budget of the system.

	Initial condition	Increase of transmitter power	Use of RZ signal	Use of cleanup polarizer and increase of transmitter power
$P1_{max}$	457 uW	1923 uW	1998 uW	1826 uW
$P0_{max}$	52 uW	306 uW	65 uW	65 uW
$P_{crosstalk}$	36 uW	109 uW	109 uW	37 uW

and 0. In order to minimize the power penalty, r_e is required to be as high as possible. However, very high extinction ratios cause many problems for the transmitter such as turn-on delay and relaxation oscillation. In general, the practical limit on r_e for a transmitter is in the range of 10 to 12 [12], which corresponds to power penalties of 1.22 and 1.18, respectively.

It is important to note that when applying (2) to our system where there are different outputs with different values of $P0$ and $P1$, it is necessary to consider the worst-case scenario. In this case, the $\text{OMA}_{\text{system}}$ and r_e of the system are determined using the minimum value of $P1$, obtained at the last stage of the system, and the maximum value of $P0$, which occurs at the first output. Based on (2) (assuming that the noise is a fixed quantity and $r_e < r_{\text{crosstalk}}$), it is clear that the system BER performance is directly controlled by the OMA. Therefore, in order to optimize BER performance, the OMA should be as large as possible.

From the optical receiver point of view, there is an upper limit on the optical power that can be received called the overload level. When the power exceeds this level, saturation effects degrade performance.

Equation (2) can be used to work out the maximum number of stages the optical signal can go through in the system. In order to do this, $P1$ minimum can be expressed in function of $P1$ maximum, $P1$ at the first output of the system, by using the relationship $P1_{\min} = \alpha^N \times P1_{\max}$, where α is the attenuation per stage, -1.40 dB or 0.72, and N is the maximum number of stages. Then, the maximum number of stages N can be obtained substituting in (2) the value of $P1_{\min}$ in the OMA and r_e,

$$N = \frac{\log\left(\left(2P_0 + Q\sigma\right) + \sqrt{\left(2P_0 + Q\sigma\right)^2 + 4\left(P_0 Q\sigma - P_0^2\right)} \Big/ 2P1_{\max}\right)}{\log \alpha}. \tag{3}$$

In (3), the value of Q is fixed to achieve a certain BER. For example, to achieve a BER of 10^{-9}, Q has to be at least 6. The noise $\sigma = \sigma_1 + \sigma_2$ is obtained experimentally and is also assumed to be a fixed value, in our experiment it is 6 uW.

5. INCREASING OPTICAL QUALITY

From the discussion in the previous section, it has been concluded that for optimum BER performance, the maximum $P1$ in the system has to be as large as possible while avoiding the overload of the detector. In addition to this, the maximum $P0$ of the system should be kept as low as possible without becoming so low that either it causes problems with the laser or becomes lower than $P_{\text{crosstalk}}$. In order to achieve these results, different techniques have been used.

Table 2 summarizes the techniques used for increasing the optical quality of the system. The first column represents the values obtained in the previous section. Substituting these values on (3), the maximum number of stages the system can support is four.

In order to increase this number, the first technique that has been used is to increase the power of the transmitter to a value where the maximum $P1$ is close to the overload level of the detector. By doing this, the $P1_{max}$ of the system has increased by a factor of 4.20, from 457 uW to 1923 uW. On the other hand, P_{min} has decreased by a factor of 5.88, from 52 uW to 306 uW. Although the maximum $P_{crosstalk}$ has also increased, from 36 uW to 109 uW, this is lower than the $P0_{max}$, and therefore the system is still under conditions for applying (3). Because of the high value of $P0_{max}$, the maximum number of stages, N, has not improved and is still four.

Therefore in order to decrease the value of $P0_{max}$, a second technique has been used, which consists in using return-to-zero (RZ) code signal instead of NRZ. The difference between these codes is that while NRZ encodes the logic one by sending a constant light intensity for the entire bit period, RZ code sends a pulse shorter than the bit period. Due to its basic pulse nature, an RZ signal has many more transitions than an NRZ signal, and less "DC" content. Although RZ signals are more difficult to produce and require more signal bandwidth, they are being used for high bit rates (40 Gb/s) because they cause less chromatic and polarization mode dispersion than the NRZ signal.

In our experiment the use of the RZ signal causes a decrease in the power of the logic zero from 306 uW to 65 uW and keeps the value of the logic one practically at the same value than before. However, the $P_{crosstalk}$ has not decreased and becomes higher than $P0_{max}$. Therefore, (3) cannot be used to determine the value of N and a third technique consisting in the utilization of a cleanup polarizer at each output of the system is used. This technique proposed in [4] improves the $r_{crosstalk} = P1/P_{crosstalk}$, of the system. Although, the use of cleanup polarizers decreases $P1_{max}$, this value can be raised again to the overload level of the detector by increasing the power of the laser.

As can be seen in Table 2, the combination of the three techniques used has increased the value of $P1_{min}$ to 1826 uW, while the $P0_{max}$ and $P_{crosstalk}$ have been kept practically to the same values as in the initial conditions. Consequently, the maximum number of stages (N) the optical signal can go through this system has increased from four to eight. Implementing the simple ring topology, eight nodes can communicate with each other using one single hop. Having said that, FSOI allows the implementation of high-dimensional networks where the number of processors that can be connected using a few optical stages can be much higher [11].

Equation (3) also shows that the attenuation per stage is a limiting factor and optimization is also required in this case. It can be seen that for example by decreasing the attenuation from 0.74 to 0.80 that the maximum number of stages the optical signal can go through in the system increases to eleven.

6. CONCLUSION

This paper has successfully shown some important properties of the OH such as reconfigurability and the use of the same channel (PBS point) for routing different signals simultaneously. These properties enable the OH to embed multiple complex topologies such as completed connected mesh or hypercube.

Moreover, the use of rapid prototyping technology has allowed optomechanical structures to be realized quickly and at low cost—in the development and characterization of the FSO channel.

Finally, after optimizing the system, especially off-the-shell LCs, it has been proven that the crosstalk caused by misdirected signal is not a limiting factor of the optical budget. As a consequence, it has been possible to use simple techniques for increasing the OMA and r_e of the system in order to increase the number of optical stages that an optical signal can go through. These techniques consist in increasing the optical power of the transmitter to the overload level of the detector, using RZ modulation code instead of NRZ code and placing a cleanup polarizer at each output of the system.

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