Free-Space Optical Interconnected Topologies for Embedded Compute Applications with Experimental Validation using Rapid Prototyping techniques.

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Abstract

Free space optical interconnects (FSOI) are widely seen as a potential solution to present and future bandwidth bottlenecks for parallel processors.

In this paper we study different topologies that can be implemented using a FSOI system called Optical Highway (OH). We propose also the use of Rapid prototyping technique as a fast and low cost tool to implement experimentally different topologies and study their properties.
Finally, the rapid prototype designed is used to calculate the maximum number of stages that an optical signal can go through in the OH without the need to be regenerated. This system cannot work without reconfigurable electronic hardware.

Subject Terms
Optical Computing
Free-space optical interconnected
Parallel topologies
Rapid Prototyping
Reconfigurable Electronics

1. Introduction

One of the major problems facing parallel computing is the increasing bandwidth required for interprocessor communication. Conventional electrical connections have fundamental physical limits [1]. The essential problem is that, for a constant connection length, the data bandwidth of an electrical link is determined by its area. As interchip communication rates increase and the area available per link reduces (as a consequence of higher connection densities) it is inevitable that the fundamental limit will become a significant problem. This scenario has been recognized by the Semiconductor Industry Association [2].

Free-space optical interconnect has been identified as a potentially important technology for future parallel-computing systems [3, 4] as it offers great potential advantages over electronic and fiber alternatives. Data rates may be as high as those of fibers but with a higher physical channel density.

However, problems relative to cost and manufacturability of the optics and opto-mechanics used in such systems are impeding their widespread acceptance [5, 6].

In this paper we propose the use of a low cost and fast technique called Rapid Prototyping for implementing new free space optical interconnected topologies.

Some of these new topologies are also presented in this paper. They are based on a free space optical interconnect technique called Optical Highway [7, 8]. This system uses polarizing beam splitter-liquid crystal (PBS/LC) stages to perform beam combination and routing functions.

We then use the Rapid prototyping structures designed to find the parameters that determine the maximum number of stages that the optical signal can go through without the need to be regenerated. This maximum is required to study properties such as scalability and latency of the topologies proposed.

2. FSOI Topologies based on Optical Highways

The Optical Highway is an FSOI system introduced in [7,8] and based on a polarization beam combination and routing technique.

Figure 1 shows the design of an unidirectional Ring Topology using the OH [9]. In this topology, polarised light is passed through a polarising beam splitter (PBS) to a quarter wave plate (QWP). On reflection at a mirror, it then passes again through the QWP and is reflected from the PBS. The twisted nematic liquid crystal (LC) can either rotate the polarised light by 90°, if switched off, or leave the light unchanged if switched on. The light then travels to the next stage of the topology where a PBS can either pass or drop the light according to the polarisation state.

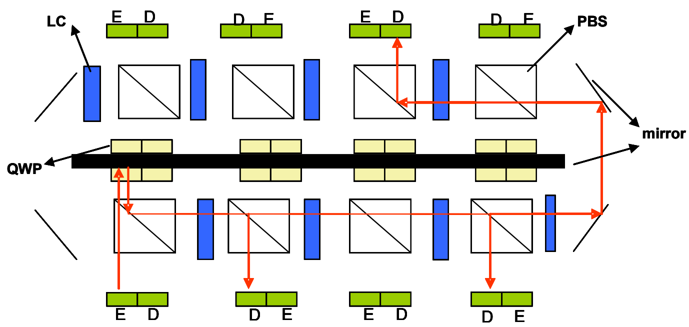
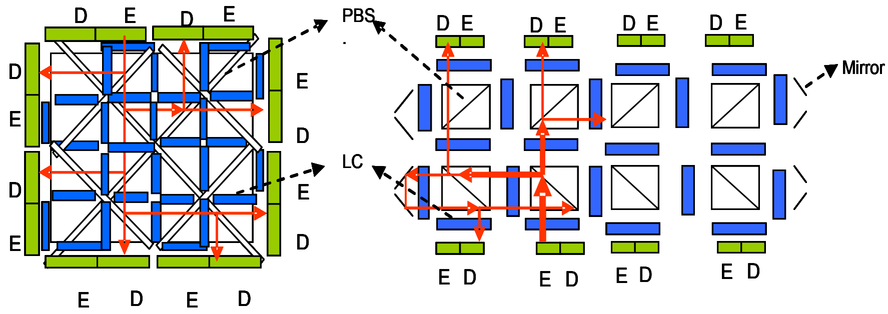


Figure 1.

In this paper we propose a modification of the previous design where both, the QWP and the mirror are replaced by one LC. This allows the implementation of new FSOI architectures with better performance.

Figure 2 shows two of these new FSOI architectures: Matrix and Optimised Ring. Both architectures present their optoelectronic nodes outside the system to easily dissipate the heat. Another characteristic is that they have been designed in order to communicate bi-directionally between any two nodes. This condition allows embedding of a completed connected topology. The use of LC's as reconfigurable elements, allows multiple topologies such as a mesh or hypercube to be embedded.



a) b)
Figure 2.

In order to see the advantages of each architecture, it has been studied the cost, in terms of number of LC and PBS, and performance in terms of diameter and bisection bandwidth. These characteristics are presented in Table 1**,** where P represents the number of Nodes, either processors or memories that the network supports.

From the results obtained in Table 1 we can see that both, the Ring and Ring optimised architecture have the same scalability factor and cost in terms of the total number of switching and links. However, the Ring optimised architecture presents better performance, since it has an inferior diameter (maximum optical distance between any 2 processors) and is a bidirectional topology.

	Matrix	Ring	Ring Optimised
# switching, LC	$P^2/2$	2P	4P
# Links, PBS	$P^2/4$	3P	P
Diameter	P-2	P+1	P/2 + 2
Bisection Width	P/2	2	2

Table. 1. Characteristics of matrix, ring and ring optimised topology.

Another advantage of the ring optimised topology is that it has been designed to interconnect optically nodes that are physically far away using only a few stages.
The Matrix architecture is the other design proposed. Although, this presents a high cost, its performance in terms of bisection width (measure of the maximum volume of

communication between two halves of the network) is higher than the other two topologies. Moreover, this architecture allows embedding a completely connected topology more easily.

As an example of the real application in parallel computing of these architectures we propose to use the ring optimised topology to implement an hybrid distributed-shared memory architecture. A set of nodes arrange in a ring optimised topology could constitute a shared memory architecture. From Figure 2 can be observed that if on one side of the architecture are placed local memories and on other side only processors, then any processor can connect with any memory and any memory can send information to any processor. Moreover, by removing the mirrors at the edge of the topology any memory and any processor has bidirectional connectivity to the network where others shared memories architecture like this can be connected.

3. Using Rapid Prototyping techniques for implementing different FSOI architectures

Rapid Prototyping (RP), also known as solid freedom fabrication or layered manufacturing, combines various methods, materials and technologies to fabricate three dimensional objects directly from a computer-aided-design (CAD) data source, eliminating the need for tooling.

RP was introduced in the 1980s as a tool that allowed the designers to improve their product and shorten the time it took to bring new products to market. However, today the introduction of new materials and lower-cost systems are pushing these same processes out of the design lab and into the manufacturing world, where they are being used to create custom parts that are production, not just prototype, quality.

Most rapid-prototyping processes are additive, building parts one layer at a time from a powder or liquid that is bonded , meted, or fused together, often with the aid of a laser. Current laser-based prototyping methods include stereolithography (SLA), selective laser sintering (SLS), and direct metal deposition (DMD).

In this paper we propose the use of RP as a fast and low cost technique for testing experimentally the FSOI topologies presented in section 2. We believe this technique can be a solution to the current problems of cost and manufacturability relative with the optomechanic of FSOI systems.

RP can be used for the first steps of the optomechanic design, where many modifications of the initial design are required.

Moreover, RP allows integrating the associated electronics much more closely with the optical components, creating more compact optomechanic structures.

The Digital Tools Manufacturing Group (DTMG) at Heriot-Watt University has recently acquired one of this 3D printer machines which has been used to explore the capabilities of this technique. Using Solid Edge CAD, it has been designed three different frames to hold a PBS plate, a LC and a laser module.

Figure 3 shows the PBS frame with the PBS plate placed on it. The PBS frame has been designed to allow the signal go through all six faces of the cube. In addition, the frame has been provided with a movable part to allow the PBS being oriented at different degrees. Although, the usual position of the PBS plate are 0° and 45° respect the input signal, the movable part allows also the active alignment of the system for fault tolerance.

Figure 4 shows the liquid crystal frames and the 45° twisted nematic liquid crystals used. It has been also fabricated with a movable part to allow rotating the LCs in order to find the right position from where they can twist the polarisation angle of the light exactly 90°.

Finally, Figure 5 shows the laser frame, which contains the laser module and its driver controller.

As we can see, each frame has been used to test different capabilities of the 3D printer machine. All the frames were created using the cost effective powder, and it took about 1-2 hours to complete the design.

It has been estimated that the translational tolerance of this design is 1mm, and the rotational tolerance is 5°. However, once the final design is decided, a metallised powder can be used that has an accuracy of 100 um. Although, this tolerance is bigger than that of traditional techniques, it is good enough to study the properties of the topologies such as attenuation per stage, polarization losses, crosstalk and maximum number of stages that the signal can go through. These properties will be studied in section 4.

However, the most important advantage of using RP is the amount of time that can be saved during the design process, where multiple corrections have to be made before a definitive design.

In this paper we propose a design where the system is made up of different blocks or cells. Each cell allows routing the incoming signal in two different directions. As they work like a "lego" pieces they can be reconfigured in many ways to create different topologies, including the matrix or ring topology. Figure 6 shows some real pictures of the assembled system.

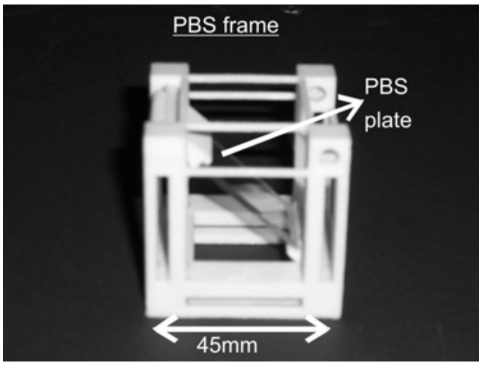


Figure 3.

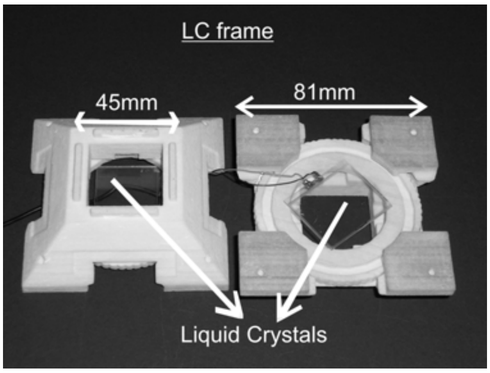


Figure 4.

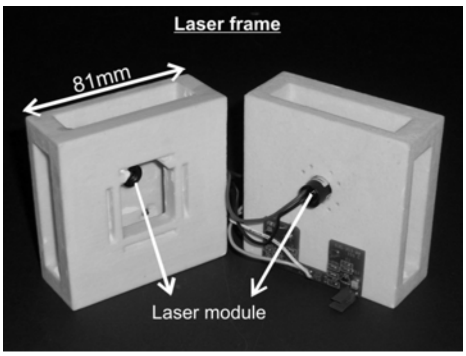


Figure 5.

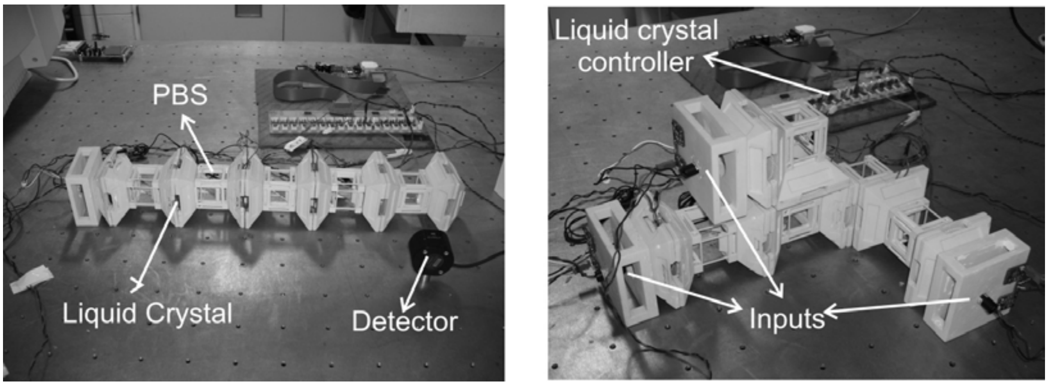


Figure 6.

4. Results

The optomechanic system designed on section 3 has been used to demonstrate experimentally the equation that establishes the maximum number of stages the optical signal can go through. The determination of this maximum allows us to define important characteristics of the topologies proposed such us scalability and latency.

The maximum number of stages is obtained by the worst case scenario, where the attenuated signal between the two furthest points on the network arrives on the detector at the same time as the miss-directed signal coming from the nearest source (maximum crosstalk).

Equation 1 shows the relation between N, the maximum number of stages the signal can go through, the attenuation at each stage A, the maximum crosstalk of the system and the Optical Signal to Noise Ratio (OSNR) required to obtain a certain bit error rate.

$$N = \frac{\max Crosstalk\ (dB) - OSNR(dB)}{A\ (dB)} \qquad \text{Equation 1}$$

The objective of this section is to find out how crosstalk and attenuation can be reduced in order to maximize the value of N. We use a model based on the matrix approach presented in [10]. This model allows exploring the polarization nature of the crosstalk and attenuated signal. It considers four sources of crosstalk: crosstalk at each state of the liquid crystal polarisation rotators, ε_0 (when LC On) and, ε_1 (when LC Off). And crosstalk in the reflected path, ε_r , and transmitted path, ε_t , of the polarising beam splitter.

The model also considers two sources of attenuation: attenuation caused by the LC, α, and attenuation caused by the PBS, β.

The LCs used in this experiment were obtained from commercially available, mass-produced, stereostropic viewing glasses produced for the PC gaming industry [11]. This was a deliberate strategy of the cheapest possible off the shelf components. As alternative to the well know PBS cube we used a wired grid polarizer (WGP) [12]. WGP can afford larger extinction ratios, larger numerical apertures and lower cost than the PBS cube.

The RP structures were used to measure the values of ε_0, ε_1 and α of the LC, and the values of ε_r , ε_t and β of the WGP. The results are listed in Table 2.

Figure 7 shows the set up of the experiment carried out using RP. The input signal was routed through different outputs by switching the appropriate LCs. Measurement of both, misdirected signal and attenuated signals were taken at each output, and we got an average attenuation per stage of −2.28 dB and a maximum crosstalk of −13.63 dB.

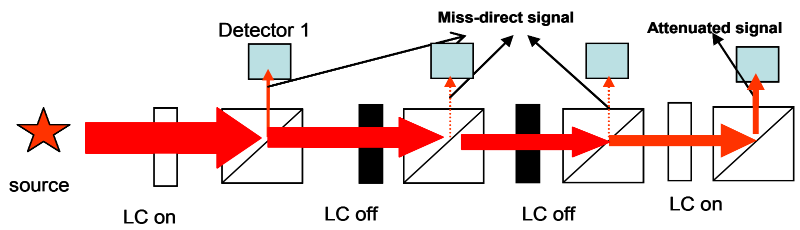


Figure 7.

Using the matrix approach on [10] we see that introducing a vertical polarized light [0,1] as input signal, the attenuated signal detected at each stage is going to be also a vertical polarised signal of value; [0, nαβ] , where n is the number of stages that the signal goes through. On the other hand, the value for the maximum crosstalk detected corresponds to an elliptically polarized light of value: [$\alpha\varepsilon_r$, $\beta\varepsilon_1$].

Using Table. 2, we obtain a theoretical result for the attenuation per stage of -2.16 dB and a maximum crosstalk of -13.89 dB.

	Crosstalk	Attenuation

Liquid Crystal	ε_0 (LC On) =0.025= -16dB	ε_1 (LC Off) =0.02= -17dB	α = 0.75= -1.2dB
PBS	$\varepsilon_t = \frac{T_s}{T_p}$ = 0.001=-30dB	$\varepsilon_r = \frac{R_p}{R_s}$ =0.033= -14.8dB	β =0.8= -0.96dB

Table 2. Experimetal values of PBS and LC parameters

These results agree with the experimental, and the difference of 0.12 dB for the attenuation and 0.26 dB for the maximum crosstalk can be attributed to the misalignment between the LC and the incoming vertical polarized signal.
Ideally, a low attenuation and crosstalk are desirable. This result can be achieved by using high quality optical devices. However, having analysed the polarized nature of the attenuation and crosstalk we find that there are others ways of achieving better result.

As we mentioned before, the attenuated signal is vertically polarised light, and the maximum crosstalk is an elliptic, almost circular light. Therefore if a high transmission clean up polarizer is used at the end of each port orientated on vertical polarization, [0, 1], the first component of the crosstalk, $\varepsilon_r \alpha$, can be extinguished. On the other hand, the clean up polarizer will introduce an attenuation α_p that has to be considered. However, this attenuation only contributes once, at the end of the system. Therefore, the signal attenuated is now [0, nαβ + α_p] and the maximum crosstalk signal is [0 , $\alpha_p \beta \varepsilon_1$].

This results have been demonstrated experimentally using a polarizer with an α_p=-1.1dB. The maximum crosstalk signal has decreased from -13.63 dB to -20 dB, while the attenuated signal decreased from -2.28 dB to -3.38 dB. Therefore the introduction of clean up polarizers at the end of each port has increased the optical budget in 5.27 dB.

Following from the study carried out above we can conclude that the use of both, clean up polarizers and high quality optical devices can contribute to increase considerably the maximum number of stages that the signal can go through before it becomes too weak.

As an example, we are going to calculate the maximum number of stages using clean up polarizers and high quality optical elements such as the one reported in Table 3. It is also going to be assumed a value for OSNR of 12, which is the minimum value to achieve a BER of at least 10^{-9} [9].

	Crosstalk		Attenuation
Liquid Crystal [10]	ε_0 (LC On)=0.013=-19dB	ε_1 (LC Off)=0.013=-18dB	α =0.93=-0.3dB
PBS [13]	$\varepsilon_t = \frac{T_s}{T_p}$ =0.02=-17dB	$\varepsilon_r = \frac{R_p}{R_s}$ =0.01=-20dB	β =0.98=-0.1dB
Polarizer [14]	ε_p =0.001=-30dB		α_p =0.9=-0.4dB

Table 3. High quality values of PBS, LC and high transmission polarizer.

Equation 1 has been modified to include the effect of the clean up polarizer and the relation between N and the quality of the parameters. The result is shown in Equation 2. where the values of the Table 3 can be substituted to obtain N=20.

$$N = \frac{\max\ Crosstalk\ (dB) - OSNR\ (dB) - attenuation\ of\ polarizer\ (dB)}{A\ (dB)} =$$

$$= \frac{\log\left(\frac{12\,(\alpha\varepsilon_p\varepsilon_r + \alpha_p\varepsilon_1\beta)}{\alpha_p}\right)}{\log(\alpha\beta)}$$

Equation 2

Figure 8 shows more clearly the relation expressed in Equation 2 between attenuation, crosstalk and OSNR when high quality optical element and clean up polarizers are used.

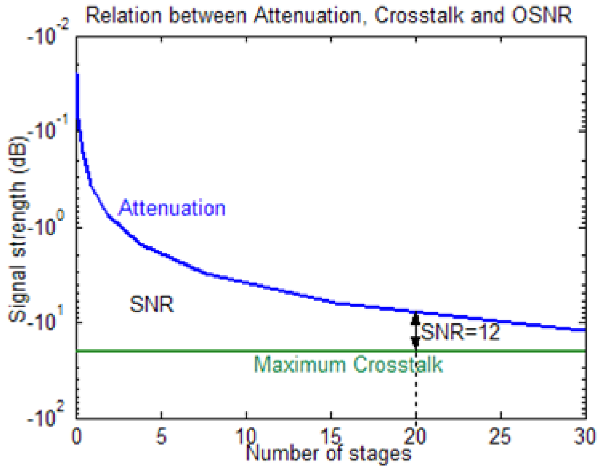


Figure 8.

5. Conclusion

This paper has presented and analysed new free-space optically interconnected architectures for reconfigurable and embedded computer applications. The matrix and ring optimised topologies proposed here use more efficiently the free space optical properties than previous designs. Traditional characteristics of static network topologies such as number of links and switching, diameter and bisection width have been used to study these new topologies.

We propose the use of Rapid Prototyping as a fast and low cost fabrication method for implementing the different topologies in order to initially study their properties with a view to a full fabrication.

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