Reprogrammable Optical Phase Array (ROPA) for use in an Agile All-Photonic Network

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Abstract: The design and simulation of a 1xN optical switch is presented. Sub-µs switching is achieved through a voltage-controlled optical phase array. Electrode voltages are provided by a high-voltage CMOS chip. Switching angles are within 2˚.

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1. Introduction

Over the past decade, there has been an evolution in the design of optical networks to match the changing needs of internet carriers. Networks are now designed not only to increase the available bandwidth, but also to decrease the overall cost and to increase the flexibility of the network. One way to achieve these goals is to migrate from an electrically switched OEO fabric to an optical switch fabric which will reduce cost, latency, and power consumption, while rendering the switch data rate and protocol independent [1-3]. By introducing the requirement for very fast optical switching in the core, dynamic provisioning and packet level switching become possible.

Currently deployed optical switching technologies are too slow for such dynamic provisioning (e.g. MEMS, thermo-optic switches). In contrast, electro-optic switching holds great promise due to its high-speed and lack of moving parts. Both waveguide and bulk electro-optic switches have significant drawbacks: in the waveguide structure the coupling losses tend to be high and in the bulk structure the required voltages approach 1kV.

In this paper, we present an optical switch design that is both fast and uses voltage levels below 300V. The design consists in applying multiple electric fields of different magnitudes across an electro-optic crystal in order to create a diffractive optical element. Both the profile and the periodicity of the device can be reconfigured by changing the voltages on the electrodes. We refer to this device as a Reprogrammable Optical Phase Array (ROPA).

2. Switch design

Optical phase arrays have been proposed for use in optical switching or beam steering for several decades. In many cases they are based on a liquid crystal design and therefore have switching speeds on the order of milliseconds [4-6], or they have a small number of electrodes which results in very high optical losses [7-8]. The ROPA design exploits the fast switching speeds of electro-optic crystals, while having a large number of electrodes to minimize the optical losses.

The ROPA switch is a diffractive optical element operating in reflection mode as shown in Fig. 1 below. The electro-optic (EO) crystal is flip-chipped to a CMOS chip that controls the electrode voltages. The incoming signal goes through the EO material and reflects off the CMOS chip, or more specifically, off of the electrodes in between the EO material and the CMOS chip.

The EO material is placed between a transparent grounded ITO electrode and an array of 64 reflective metal electrodes. The electrodes are 20µm wide with a 5µm gap between them to prevent arcing. Voltages are applied to the metal electrodes and a pattern of different refractive indices is created in the electro-optic material. The resultant is a diffractive element that can be reconfigured by changing the applied voltages. The CMOS chip is made from a high-voltage CMOS process capable of both low-voltage and high-voltage digital design [9]. Flip-chipping the crystal to the CMOS chip is an integral part of the design, as it allows for the control of large number of electrodes with a fine pitch. The maximum voltage that can be provided by the chip, 300V, therefore becomes a design parameter for the ROPA device.

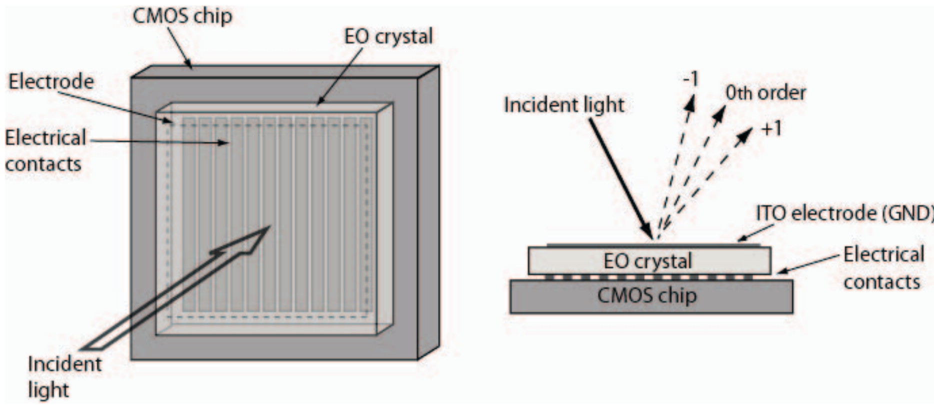

Fig. 1. ROPA switch

3. Choice of electro-optic crystal

The electric field is applied across the thickness of the crystal, which induces an index change in the EO crystal. The magnitude of the index change must be sufficient to introduce a 2π phase shift to the incoming light. For most commonly used EO crystals, such as $LiNbO_3$, the strongest electro-optic coefficient is the r_{33} coefficient. However, this coefficient is not appropriate for the ROPA design, since the light does not propagate perpendicularly to the electric field. Ideally, a crystal with a strong r_{13} coefficient would be used, but no such crystal is commercially available. $BaTiO_3$ crystals have a very strong r_{15} coefficient (1700 pm/V), and are therefore used for the ROPA design. In order to minimize the reflections off of the crystal, the incoming TM polarized light is at an angle of incidence that is close to the Brewster angle.

The crystal dimensions are 5mm x 5mm x 0.5mm. The thinner the crystal, the larger the electric field through the crystal, and consequently the smaller the voltage required for a 2π phase shift. With a thickness of 0.5mm, the voltages needed for a 2π phase shift are less than 300V when working at 1310nm.

One drawback of using $BaTiO_3$ as the electro-optic material for the switch is that the tetragonal $BaTiO_3$ single crystal will change phase to orthorhombic when the temperature is lower than 13°C, or to cubic when it is higher than 125°C. When it returns to its tetragonal state at room temperature, it has lost molecular polarization and is unusable without re-poling. It is therefore necessary to keep the crystal within this temperature range and that during transportation, processing, operation, and storage.

4. Simulations

In order to model the optical performance of the phase array, electrode voltages are applied as boundary conditions to the electro-optic crystal and the electric field distribution is computed using a finite-differences method. Once the electric field distribution has been found, the resulting indices of refraction are calculated at each point in the crystal using the electro-optic tensor, and that for a given optical path through the material. Due to the anisotropic nature of the crystal, the index sampled by light once reflected from the bottom electrodes will be different from that before reflection. In order to circumvent this added difficulty in the subsequent simulations, the reflection structure is unfolded into a transmission structure, through which light propagation is unidirectional.

The computed index distribution for the unfolded structure is transferred into the two-dimensional rigorous coupled wave analysis (RCWA) tool. Due to the nature of RCWA, the index profile needs to be segmented in both spatial directions into uniform index segments. The number of segments depends on the index profile and care must be taken to ensure that for a given number of segments the computation is convergent. The transmission efficiencies of the structure are obtained in the RCWA.

In order to optimize the voltages applied to the structure for a desired operating wavelength, incidence angle and electrode configuration, the entire model is executed in a simulated annealing (SA) optimization process. This optimization uses the efficiency in the desired order(s) as the merit function with the voltage variation linked to the SA temperature parameter. The SA optimization can be applied to all of the electrodes simultaneously or to one electrode at a time, and this can be done repeatedly for a further refinement of the design.

5. Results

The graph below shows the simulated efficiencies of the ROPA device. The x-axis indicates the number of electrodes in one period of the grating. As the number of the electrodes increases, the ability to tailor the profile of the grating increases, leading to greater diffraction efficiencies. However, an increasing period leads to a reduction in the deflection angle. When working at 1310nm and with between 3 and 8 electrodes per period, the deflection angles range from ±0.38˚ to ±1.0˚.

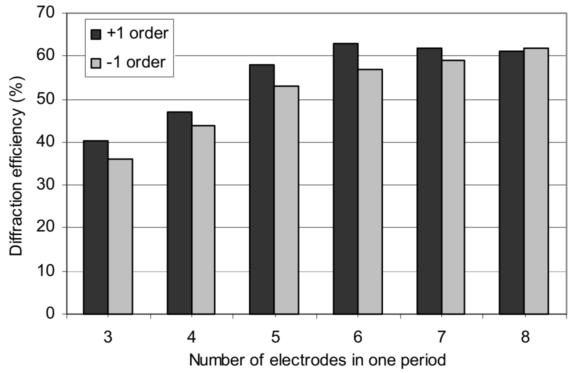

Fig. 2. Diffraction efficiencies for device used at 1310nm

The number of output ports for a ROPA switch is depended on the divergence of the impingent light, and the spatial separation between the outputs. For example, a 1x6 switch is realized by tuning the electrode voltages for either the +1 or -1 orders, for a grating consisting of 3, 5, or 8 electrodes per period.

6. Experimental results

The high-voltage CMOS chip is currently being fabricated, and will provide 64 voltages from 0 to 300V, with a 4.7V resolution. Simulated electronic switching times are less than 8.7µs. Poled $BaTiO_3$ crystals have also been obtained, and we are currently depositing electrodes on them that are suitable for the subsequent flip-chip process. Experimental results will be presented at the conference.

7. Conclusions

The ROPA switch is a fast, 1xN optical switch, suitable for use within an agile all-photonic network. The simulated diffraction efficiencies range from 36% to 64%, with up to a ± 1.0˚ switching angle.

8. References

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