Reprogrammable Optical Phase Array (ROPA) used as a 1x6 space switch

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Abstract --- **The design, simulation and testing of a 1x6 optical switch is presented. 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˚.**

I. INTRODUCTION

Agile all-photonic networks require fast spatial switching at the core to allow for dynamic provisioning and packet switching [1]. Electro-optic switches fulfill these requirements, but both waveguide and bulk electro-optic switches have significant drawbacks: in the waveguide structure the coupling losses can be high and in the bulk structure the required voltages approach 1kV [2].

In this paper, we present a switch design based on a Reprogrammable Optical Phase Array (ROPA) that is both fast and that uses voltage levels below 300V. Many existing optical phase arrays are either based on a liquid crystal design, and therefore have switching speeds on the order of milliseconds [3,4], or they have a small number of electrodes which results in very high optical losses [5,6]. The ROPA design exploits the fast switching speeds of electro-optic crystals, while having a large number of electrodes to minimize the optical losses.

II. SWITCH DESIGN

The ROPA switch is a reflective, diffractive optical element and is shown in Fig. 1. The electro-optic (EO) crystal is flip-chipped to a CMOS chip that controls the electrode voltages. The incident light goes through the EO material and reflects off of the electrodes in between the EO material and the CMOS chip.

The EO material is placed between a transparent grounded indium tin oxide (ITO) electrode and an array of 64 reflective metal electrodes. The electrodes are 20μm wide with a 5μm gap between them to prevent arcing, which gives a fill factor of 80%. Voltages are applied to the metal electrodes and a pattern of different refractive indices is induced in the electro-optic material. Both the profile and the periodicity of the device can be reconfigured by changing these voltages. The CMOS chip is made from a high-voltage CMOS process capable of both low-voltage and high-voltage digital design [7].

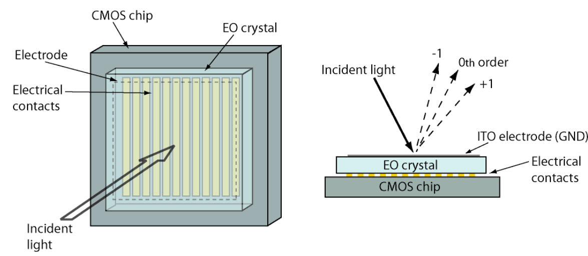

Fig. 1. ROPA switch, top view and side view

III. 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. $BaTiO_3$ crystals have a very strong r_{15} coefficient (1700 pm/V), and are therefore chosen for the ROPA design. The crystal dimensions are 5mm x 5mm x 0.5mm. For this thickness, the voltages needed for a 2π phase shift are less than 300V when working at 1310nm.

One drawback of using $BaTiO_3$ as the EO crystal for the switch, is that is must be kept within 13°C and 125°C. $BaTiO_3$ 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.

IV. 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 unfolded index profile for a single grating period consisting of 4 electrodes (a period of 100µm) is shown in Fig. 2.

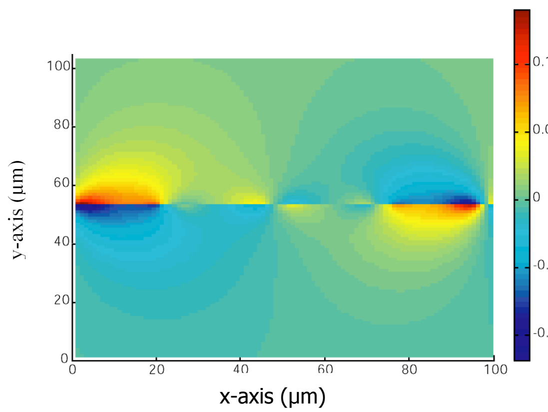

Figure 2. Unfolded index profile of center of BaTiO3

The computed index profile for the unfolded structure is transferred into a two-dimensional rigorous coupled wave analysis (RCWA) algorithm. This index profile is 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, 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.

Fig. 3 shows the simulated diffraction efficiencies of the ROPA device, working at 1310nm, which range from 37% to 63%. The x-axis indicates the number of electrodes in one period of the grating. As the number of 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 using 3 to 8 electrodes per period, the deflection angles range from ±0.38˚ to ±1.0˚. When working at 1550nm, the diffraction efficiencies range from 39% to 62%, but the required maximum voltage is 355V.

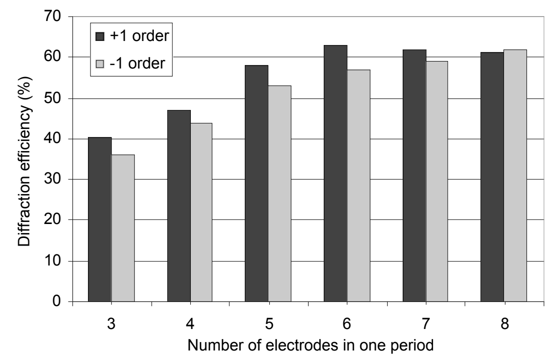

Fig. 3. Diffraction efficiencies for device used at 1310nm

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. 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.

VI. Experimental Results

The high-voltage chip was fabricated in DALSA Semiconductor's 0.8µm CMOS/DMOS HV process technology. The design consists of an array of 64 Digital-to-Analog (DAC) converters. Each DAC independently provides 64 voltages from 0 to 300V, with a 4.7V resolution. Experimentally measured rise times are less than 5.4µs, and the fall times are less than 16.2 µs.

A process to deposit flip-chip compatible Al/Ti/Au electrodes onto poled $BaTiO_3$ crystals has been developed, and crystals were flip-chipped onto test chips. The optical performance of the device is currently being tested and will be presented at the conference.

7. Conclusion

The ROPA switch is a fast (16.2µ), low-voltage (<300V), 1x6 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.

References

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