Direct Digital Control of an Efficient Silicon+Liquid Crystal Phase Shifter

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***Abstract*—We demonstrate a phase shifter based on a silicon slot waveguide infiltrated with liquid crystal. We achieve a phase shift of 73 π for a 5V drive voltage, with a voltage-length product of 0.022V·mm around 1V. We can drive the phase shifter directly with a 1V, duobinary pulse-width-modulated signal, allowing direct digital CMOS control of an analog optical phase shifter.**

I. INTRODUCTION

Optical phase shifters are essential building blocks for tuning, switching or modulation. For modulation the first criterium to satisfy is operation speed, but for tuning and switching the power consumption is a greater concern. Thermal tuning is efficient, but power hungry. Carrier-based effects are very fast but weaker. Silicon-organic hybrids based on slot waveguides can achieve much higher electro-optic efficiencies that can be tailored with a proper choice of organic material [1]. We present a phase shifter based on a slot waveguide infiltrated with liquid crystal, which have a huge anisotropy, and a very strong (but rather slow) electro-optic effect. In combination with silicon photonics they can be used for very efficient tuners [2]. A liquid crystal in a slot waveguide enhances this effect by increasing the confinement of light in the LC while at the same time increasing the electric field strength between the LC electrodes, dramatically reducing the modulation voltage [3].

A second aspect is the control of the phase shifter. When electrically driven, the accuracy of the phase shifter is closely related to the accuracy of the digital-to-analog converter (DAC) that provides the drive voltage or current. This can actually be the limiting factor unless high-quality DACs are used, especially in combination with a low driving voltages. DACs also consume power and chip real estate. We demonstrate a direct digital control of a liquid crystal phase shifter using fast 1V pulse-width-modulation control. The relatively slow response of the liquid crystal will average this digital signal in an analog phase shift.

II. CONCEPT AND DESIGN

The phase shifter is part of a Mach-Zehnder modulator designed by Karlsruhe Institute of Technology and fabricated in IMEC. The device consists of an MMI splitter and combiner and 1mm long slot phase shifters in both arms. The slot is contacted through a thin doped silicon slab, and connected to electrodes using tungsten vias and copper wiring. The backend stack is etched back down to the waveguide. The resulting cross section is drawn in Fig. 1.

The liquid crystal is applied on the waveguide and allowed to spread across the modulator. It is difficult to verify the filling of the slot, but from the experiment we can assume than the infiltration is quite good. Applying a voltage over the rails of the slot waveguide will realign the LC molecules, changing the effective index of the TE mode. The phase shift will translate in an intensity change at the output of the MZI. We only drive one arm of the MZI modulator, grounding the central electrode and one of the outer electrodes. The phase shifter is operated in alternating current (AC): otherwise ion impurities in the LC will accumulate, negating the electric field. The operation frequency should be between 30kHz and 1MHz. The upper limit is dictated by the choice of liquid crystal (E7) which gradually loses its anisotropy beyond beyond this frequency.

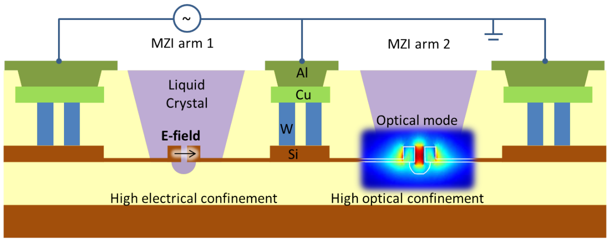

Fig. 1. Conceptual drawing the device under test.

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III. Device Characterization

A. Phase response

To characterize the static response, we swept the amplitude of the AC signal from 0V to 5V. We measured the intensity modulation of the MZI, recording the peaks and zeros corresponding to a 0 and π phase difference. Fig. 2 shows the phase modulation (in multiples of π): we achieved a modulation of 73π for 5V amplitude, and the effect saturates, indicating a complete realignment of the LC. The highest modulation efficiency lies between 0.2V and 2.5V, with a differential phase shift of $d\phi/dU = 44.53\pi/V$ around 1.0V. This corresponds with the very low voltage-length product of 0.022 V$\cdot$mm.

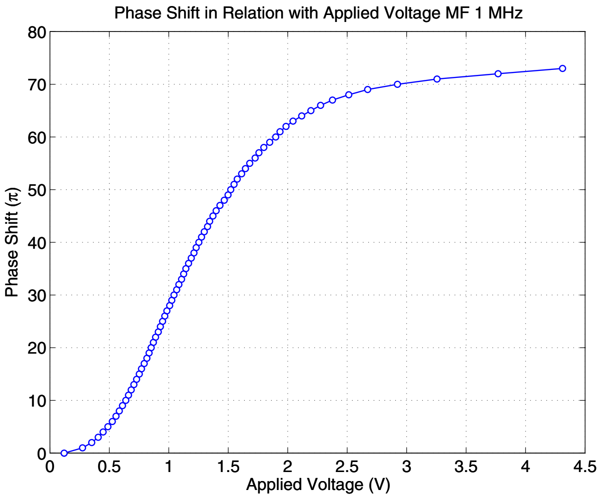

Fig. 2. Phase shift as a function of control voltage. A phase shift of 73 π is achieved at drive voltage of 5 V.

B. Switching time

We measured the switching time by switching the device from an off-state near 1.0V to a nearby on-state, and back. For larger voltages, we go through multiple minima and maxima before the signal settles. The switch-on and switch-off time are between 1.5 ms and 2.5 ms, independent of the drive voltage. We can speed up the switching time by applying an overdrive or pre-emphasis. When we apply a 4V overdrive, we can reduce the switching time to 100μs. Such an overdrive is difficult to apply for a reduction in voltage, where switching is limited by the relaxation time of the LC.

IV. Digital Driving with PWM

Instead of an analog drive voltage, we now directly apply a digital drive voltage to the phase shifter. We use fast pulse-width modulation (PWM), and the LC will respond only to the RMS of the voltage. The precision can be controlled by the word length, as long as it is much shorter than the switching time. We used a word rate of 25.6kHz. Because the liquid crystal requires an AC signal (net zero voltage), we use a duobinary encoding where pulses are alternatingly positive or negatively. This is shown in Fig. 3.

When we sweep the duty cycle of the PWM in steps of 0.5%, we can again record the output of the MZI. The observed response (phase shift obtained for a given duty cycle) for a 1.0V drive is shown in Fig. 4, with a pulse frequency of 25.6KHz. We observe a 32π phase shift.

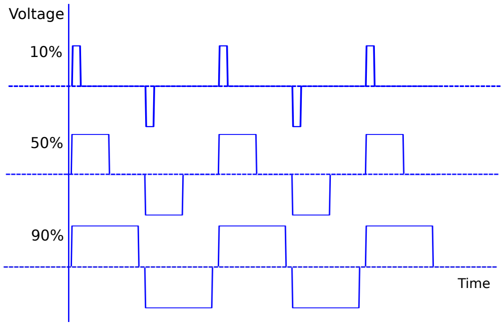

Fig. 3. Duobinary PWM drive signal.

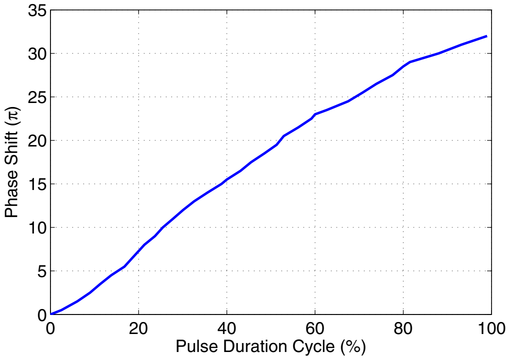

Fig. 4. Phase shift with increasing duty cycle of the PWM drive signal at 1.0V. We observe a phase shift of 32 π.

The power consumption of the device is extremely low and difficult to measure directly. We could establish an upper limit of 2nW. As the power consumption is related to the (dis)charging of the slot capacitor, it should be constant during the PWM modulation scheme.

V. Conclusion

We demonstrated a liquid crystal on silicon phase shifter with a very high modulation efficiency of 0.0211V$\cdot$mm and a direct digital control using duobinary pulse-width modulation. The device is overdimensioned and achieves a 32π phase shift with a 1.0V drive. This makes it possible to reduce the device length from 1mm to 70μm.

Acknowledgement

Part of this work was supported by the European Union through the FP7-SOFI project.

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