

Angle Selective Enhancement of Beam Deflection in High-Speed Electrooptic Switches

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Abstract—Fast electrooptic (EO) deflector switches (DSs) have high potential for applications in optical burst transport networks. EO properties of active materials used in the DSs can impose some limitations on their beam deflection efficiencies. Using a test setup with planar silica waveguide microlens arrays, thin-film ferroelectric oxide beam deflectors, and glass volume Bragg gratings, we demonstrate that the beam deflection angle can be increased by more than a factor of 5 for the same switching voltages. The technology enables significant performance improvement of the fast EO DSs.

Index Terms—Beam deflectors, electrooptic (EO) switches, ferroelectric thin films, microoptics, PLZT, volume Bragg gratings (BGs).

I. INTRODUCTION

OPTICAL switching with submicrosecond speeds has been a subject of active research and development in recent years for utilization in optical burst transport networks [1]–[4]. The required switching times of less than 1 μ s can be achieved using electrooptic (EO) materials as active elements in the switches. EO switches based on light beam spatial deflection were demonstrated in recent years in planar [1], [2] and bulk [3] configurations. A variety of bulk and thin-film EO materials [1]–[6] such as, for example, lead lanthanum zirconium titanate (PLZT) [1], [5] can be used for light beam deflection in switches; however, thin films enable significant reduction of the switch driving voltages. A schematic of a thin-film planar deflector switch (DS) is shown in Fig. 1. A survey of the planar DS design, fabrication, and operation can be found in [1].

In brief, the switch consists of the input and output waveguide (WG) microlenses, which enable handling of collimated light beams propagating through the slab WGs of the deflector chips, and the slab expander between the deflectors. The input deflector with a thin EO film can steer the light beams laterally by applying voltages to the prism-shaped electrodes. After propagation in the expander slab, the beams enter the output deflector which redirects them into the corresponding output lenses. The collimated beams can cross in the slab WG without interference, and thus the switch operation is nonblocking. The deflector can

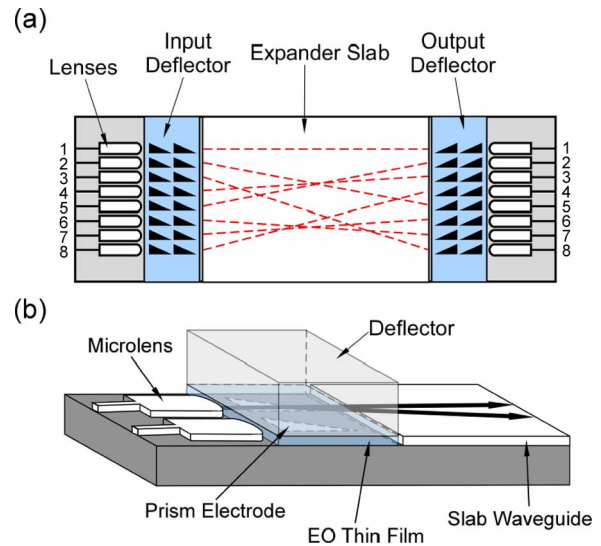


Fig. 1. Schematic of a planar DS with EO deflectors. (a) Top view of an eight-channel switch; and (b) 3-D view of the input deflector assembly.

be assembled with the EO film down [1], as shown in Fig. 1(b), or can also be mounted with the film up [2]. Switching to different output channels is realized by either changing the voltage on the prism electrode or by applying voltage to a different number of sequential prism electrodes.

Limited deflection efficiencies of the deflector elements can impose a significant challenge for DS operation. Although bulk EO materials can have EO coefficients (EOCs) of more than 100 pm/V, the thin-film material's EOCs typically do not exceed 50 pm/V [1], [2], [4]–[6]. Limited EOCs and, thus, deflection efficiencies result in high switching voltages as well as long slab expanders required for sufficient beam separation at the output ports. For example, an eight-channel planar DS with the 600- μ m channel pitch [1] has the expander slab length of 80 mm. In this letter, we demonstrate that selective angular deflectors (SEADs) formed from glass volume Bragg gratings (BGs) can significantly increase the deflection efficiencies of the switches and, therefore, enable reduction of the switch voltages and device dimensions.

II. RESULTS

The DS operation with SEAD can be explained with the schematic of Fig. 2, which shows the input part of a DS module. The planar WG microlenses and the deflector chip are similar to those shown in Fig. 1 for a regular DS. A transmitting volume BG is placed right after the deflector chip so the light beam passes through it before entering the expander. Transmitting

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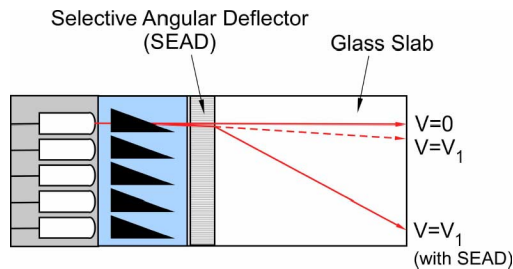


Fig. 2. Operation schematic of DS with SEAD.

volume BGs are angle selective and only redirect the light beams meeting the grating's Bragg condition. In Fig. 2, the $V = 0$ beam passes through the BG unaffected. Without SEAD, the beam would be deflected at a small angle Δ when voltage V_1 is applied. If the SEAD is designed so that the BG's input Bragg angle is equal to Δ , then the beam will be further deflected at the final angle Δ_f which is multiples of the original angle Δ . All other beams entering SEAD at non-Bragg angles will pass through the grating without amplification.

Input and output angles, angle amplification strength, angular and spectral sensitivities of SEAD gratings can be varied in a wide range by adjusting the grating parameters such as refractive index contrast δn , spatial frequency f , and grating thickness t [7]. For example, the BG's angular selectivity is approximated by $\Delta_{\Theta_{FWHM}} \sim (ft)^{-1}$ and, thus, changing the grating thickness t or spatial frequency f enables variations of the angular selectivity in a wide range from 0.01° to several degrees. Similar dependence is valid for BG spectral selectivity which can be tuned from 0.1 to 100 nm [7]. The angle amplification strength can also be varied from a few to hundreds of times. One BG can enhance the deflection by only a given fixed factor. Thus, different gratings should be stacked in the light pass to steer beams to different output ports. It was previously demonstrated that numerous volume BGs can be recorded in the same volume without affecting each other [8].

For demonstration of the deflection angle amplification, the experimental setup schematically shown in Fig. 3(a) is used. The microlens array, deflector, and SEAD with a glass slab are assembled on microstages and aligned so that the WG cores are leveled. The 1550-nm light is launched through a single-mode optical fiber into the channel WGs of the microlenses. An IR camera captures the outgoing beam images at the output edge of the slab.

The microlens arrays were fabricated in a silica-on-silica planar technology. The microlens design, fabrication, and properties were reported in detail in [9] and [10]. The lenses are formed on silica or silicon substrates by deposition and etching of three silica layers: lower cladding, core, and upper cladding. The 5- to 8- μm -thick WG core layer is doped with Ge which increases its refractive index by 0.2%–0.5%. A scanning electron microscope (SEM) image of the microlens in Fig. 3(b) shows the shape of the microlens front side, which is formed by reactive ion etching and enables lateral collimation of light beams with widths of 200–500 μm [9]. The light is confined vertically in the slab WG.

The deflector element shown in Fig. 3(c) is $10 \times 12 \text{ mm}^2$ in size and consists of a 10- μm -thick PLZT film grown on a

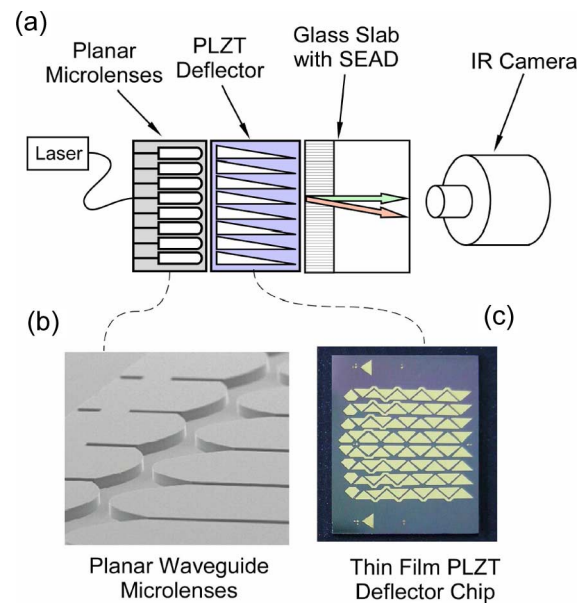


Fig. 3. (a) Test setup for demonstration of the SEAD operation. (b) SEM image of WG microlens array used in the experiment. (c) Thin-film PLZT deflector chip with eight-channel array of prism deflectors.

Nb-doped SrTiO₃ (Nb:STO) substrate by solid-phase epitaxy [5]. The PLZT slab WG is formed from three layers: 3- μm -thick lower cladding, 2- μm -thick WG core, and 5- μm -thick upper cladding. The propagation losses of the WG are less than 1 dB/cm. The core and cladding films have different La content, which provides the WG refractive index difference. The EOC of the film is about 40 pm/V with very weak dependence on the light polarization [1], [5]. The Nb:STO substrate is conductive, and thus serves as a lower electrode. The top electrodes, seen in Fig. 3(c), are formed from a thin gold film patterned by wet etching.

Glass volume BGs for SEADs are formed in a photo-thermo-refractive (PTR) glass, which is a sodium-zinc-aluminum-silicate glass doped with silver, cerium, and fluorine. The PTR glass technology is well developed¹ and details on the glass fabrication and BG formation in PTR glasses can be found in [11]. The BGs used in this work were recorded by exposure to an interference pattern of a He–Cd laser operating at 325 nm, with dosages less than 1 J/cm². The BGs have spatial frequency of 110 mm⁻¹ and a thickness of about 1 mm. Fig. 4 shows the angular dependence of the light intensity diffracted by the BG with a diffraction efficiency of about 97%. The SEAD optical loss is less than 1%.

In the test setup of Fig. 3(a), a 20-mm-long glass slab with BG is mounted next to the deflector chip. The slab height is about 0.8 mm. The vertical light divergence in the glass slab is not important since only lateral beam deflection is measured. In the test experiments, the air gap between the microlens array, deflector, and BG is about 5–10 μm . The angular alignment sensitivity of the grating is determined by the angular selectivity of the BG shown in Fig. 4.

A near-field microscope with an IR camera captures the beam position at the slab output. To evaluate quantitatively the an-

¹For more detail, refer to <http://www.optigrate.com>.

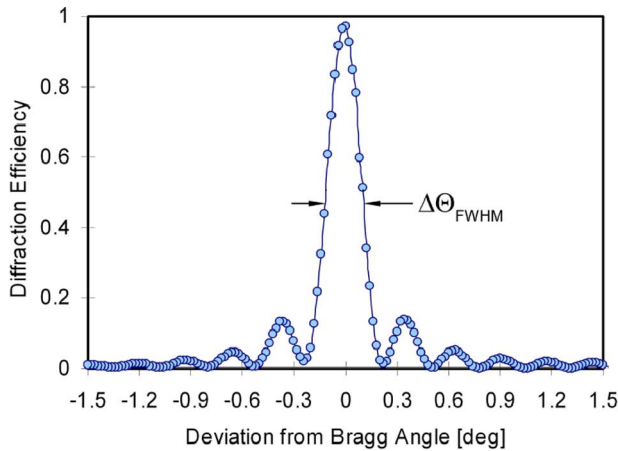


Fig. 4. Measured angular dependence of transmitting BG at 1550 nm used for enhancement of beam deflection angle.

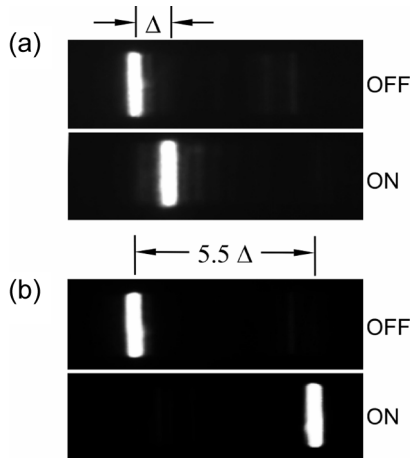


Fig. 5. Output beam positions captured with an IR camera at the edge of the glass slab. Beam deflection with 40 V applied to the prism electrodes, (a) without and (b) with SEAD in the light pass. Δ is about 1.1° .

gular enhancement, the beam deflection is measured in SEAD and no-SEAD configurations. The no-SEAD configuration is achieved by a slight angular misalignment of the glass slab with BG relative to the beam, so the Bragg condition is not met. In this case, the transmission media and the length of the sample are identical. The same voltage of 40 V is applied to the prism electrodes for switching in the no-SEAD and SEAD configurations and the results of the beam deflection measurements in both cases are shown in Fig. 5(a) and (b), correspondingly.

The beam deflection without SEAD is shown in Fig. 5(a). The beam positions with the driving voltage ON and OFF are presented in the top and bottom panels of the figure, respectively. With the voltage $V_1 = 40$ V, the beam deflection at the output is approximately $\Delta \sim 1.1^\circ$. Fig. 5(b) shows the beam deflection with SEAD for the same driving voltage of 40 V. The beam deflection is measured to be approximately 6° , which is about 5.5 times larger than in the no-SEAD configuration. It is not seen in the figure but when the voltage increases to 50 V, the deflected beam returns back (moves to the left) to a position just

slightly larger than the original Δ . The results clearly demonstrate that SEADs can selectively amplify deflection angles in DS. The switching speeds of the devices were measured to be less than 300 ns [2]. The speed is mostly limited by the capacitance of the electrodes and can be reduced by decreasing the electrode size. The electrode size reduction can be facilitated by SEADs due to much larger deflection efficiencies, which will lead to faster switching. Integration of SEADs in DSs can provide a strong boost to the switch performance and at the same time can reduce the device cost.

III. CONCLUSION

We have demonstrated that glass volume BGs can be used to enhance deflection angles with high angular selectivity. The evaluation experiments were conducted in a test configuration using planar WG microlenses, thin-film PLZT EO deflectors, and BGs with slab expanders. The beam deflection angle increase by more than a factor of 5 was demonstrated for the same switch driving voltage.

Integration of SEADs in DS can improve the switch performance in terms of lower driving voltages, i.e., faster or simpler driving circuitry; smaller device dimensions, i.e., more devices per wafer; faster switching; etc. Currently, glass volume BGs are not available in Si-based planar technologies and, therefore, they can be used only for bulk-type DSs [3], or for hybrid integration of planar DS [1], [2]. Development of planar technologies for PTR glasses will make full integration of SEADs feasible.

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