Invited Paper

High-speed Electro-optic Switches for WDM Applications

Suning Tang, Bulang Li, Xinghua Han, and Jinzhi Ni
Radiant Research, Inc.
3005 Longhorn Blvd., Suite 105, Austin, Texas 78758

Ray T. Chen
Microelectronics Research Center
Department of Electrical and Computer Engineering
The University of Texas at Austin, TX 78758-4445

ABSTRACT

We present an electro-optic switch based on a guide-wave electro-optic beam deflector in conjunction with multiplexed waveguide holograms for wavelength-division-multiplexing applications. The presented switching device functions as a fully transparent wavelength selective optical cross connect for fiber optic transmission systems. The demonstrated device consists of only one driving electrode and does not require any moving component. It is capable of not only switching an optical beam but also reconfiguring many wavelengths from one fiber to many other fibers.

Keywords: Electro-optic Switches, Electro-optic Prisms, Polymer-based Waveguides, Optical Cross-connects, Wavelength Division Multiplexing, Multiplexed holograms

1. INTRODUCTION

The exploding demand for bandwidth in data and telecommunications networks has been met by breaking increases in optical fiber capacity, driving by wavelength division multiplexing (WDM) and optical fiber amplifier technologies. Switch technology, however, fallen behind as transmission in the electric domain, has proved to be a significant bottleneck. Current electronic switches are stretching to reach multi-gigabit speeds, while optical technology is promising terabits on a single fiber. One promising solution is to keep network traffic in the optical domain, which eliminates the need for complex and expensive switching electronics in the optical layer. In other words, optical switches may find wide applications in future wideband fiber optic communication networks[1,2].

The optical switches offer many attributes, including optical transparence, non-blocking cross connection, protocol independence, wavelength independence, WDM compatibility and no bandwidth limit. More importantly, it can reconfigure wideband signal without the need for optical-to-electrical and electrical-to-optical conversion. So far, a variety of technologies in existence or under development include optomechanical, micro-electro-mechanical fiber-optic[3], liquid crystal gratings[4,5], and electro-optic switch[6]. However, it has been found that these methods may suffer from various limitations such as low speed, high insertion loss, complicated fabrication scheme, and requirement of multiple driving sources.

In this paper, we present a polymer-based electro-optic switch based on a guide-wave electro-optic beam deflector in conjunction with multiplexed waveguide holograms. The presented device combines advantage of a thin-film electro-optic (EO) prism array and multiplexed waveguide holograms, capable of switching multiple optical channels and multiple wavelengths using a single electrode and a single electrical driving source. No any moving component is required. Such a device is advantageous whenever there is a need for high-speed, reliable, compact, low-loss and low-power optical switching and wavelength switching.

2. DEVICE CONCEPT

There are four building blocks required for constructing the presented optical switch for WDM applications. They a (1) the polymer-based planar waveguide, (2) the waveguide lens, (3) the guided-wave electro-optic prism array and (4) t multiplexed waveguide hologram. Fig. 1 shows the schematic of the polymer-based electro-optic switch for WD applications. An optical incident beam from an optic fiber is launched into the polymer-based planar waveguide using dire end-butt coupling. A holographic waveguide lens is employed for collimating and focusing the incident beam, providing tl lateral confinement of the incident beam. The propagation direction of the incident beam is controlled by an array of electr optic prisms, which deflects the laser beam based on electro-optic effect. The multiplexed hologram diffracts the deflect incident beam, consisting of two optical wavelengths of λ_1 and λ_2, into two beams of the wavelength λ_1 and λ_2, respectivel It should be noted that the presented optical switching device could be scaled up by increasing the number of multiplexe holograms and the number of holograms multiplexed if multiple wavelengths and multiple fiber-optic channels are involved.

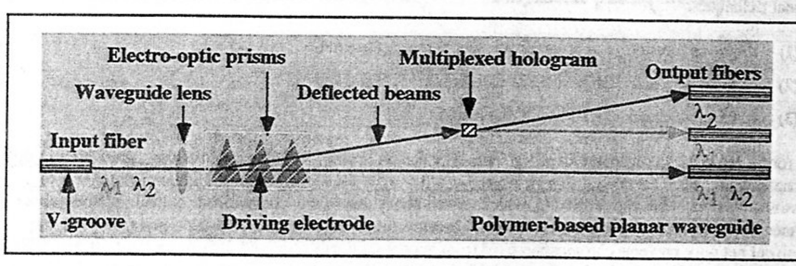

Fig. 1. Schematic diagram of an optical waveguide switch based on electro-optic prisms and a multiplexed holographic element.

One of the distinguishing features of the proposed device is that electro-optic prisms are formed in a polymer-base planar waveguide. The beam deflection is controlled by applying an electric voltage to the electrode cross the prisms based o the electro-optical effect. Such a polymeric thin-film waveguide structure results in a very low driving voltage for high-spee operation. Employing cascaded electro-optic prisms in an array further reduces the driving voltage by adding up the deflectio of each prism. Only one electric driving source is required to control the 1xN optical switching and wavelength switchin through a uniform face-to-face electrode. No any moving component is required. Another distinguishing feature of th presented device is the multiplexed volume waveguide holograms. These multiplexed hologram serves as a set of wavelength division-demultiplexers. More than 60 holograms can be multiplexed within a small region in a planar waveguide, which ca provide more than 1-to-50 individually diffracted beams with selected wavelength. An array of multiplexed holograms can b easily fabricated with diffraction efficiency close to 100%.

3. POLYMER-BASED ELECTRO-OPTIC WAVEGUIDES

Compared with their inorganic counterparts, nonlinear optical (NLO) polymeric materials have several well-recognized advantages such as thin-film format, large electro-optical effect, compatibility with different substrates, ease o fabrication, and low cost. Another unique advantage of electro-optic polymer is its low dielectric constant and low dispersio of dielectric constant. As a result, many NLO polymers have been synthesized in recent years[7-11]. Some NLO materials hav achieved long term stability satisfying the military requirement of -55 °C to +125 °C[12]. A very wideband operation (up t 110 GHz) can be easily obtained in polymer-based electro-optic devices.

The achievement in realizing low-loss electro-optic waveguides using photolime gel polymer motivates us t employ such a unique material as a multifunctional polymer for integrating both the electro-optic prisms and waveguid holographic elements as a wavelength selective optical switching device. We have selected photolime gel polymer as the hos polymer doped with the chromosphere red for obtaining electro-optic effect and ammonium dichromate for obtaining photorefractive effects[13-15]. Gelatin has been classified as a super polymer because of its extraordinary chemical and physical properties and its molecular structure[16]. It can be dissolved in many organic and inorganic solvents to form a proper solution that can be easily spin-coated on any substrate of interest. When the solution is dry, the photolime gel polymer becomes a rigid glass film that shows very little absorption and optical scattering.

We have developed a mixed solvent technique for effectively doping of chromosphere red into gelatin using a mixed solvent. Since chromosphere red is soluble in most organic solvents while gelatin and ammonium dichromate are soluble in water but not organic solvents, it is reasonable to use a mixture of water and an organic material as the solvent. In order to prevent the microscopic clustering phenomena, we believe that the water solvent should be evaporated before the evaporation of the organic solvent. To verify this concept, we selected ethylene glycol ($HOCH_2CH_2OH_2$) as the organic solvent because it mixes very well with water, and has evaporation temperature of 197 °C, which is much higher than that of water[17]. Based on this mixed solvent, high quality electro-optic films without microscopic clustering have been prepared with the ratio of chromosphere red to gelatin up to 30%. The mixed solvent method (water and ethylene glycol), has many advantages over conventional techniques:

(1) to prevent clustering or crystallization of chromosphere red,

(2) to promote a thorough mixing of chromosphere red and gelatin,

(3) to improve chemical stability of the resulting polymers.

We have found that the chromosphere doped gelatin after electric poling is stable against moisture, which is different from conventional gelatin. They are not soluble in water for at least 10 days, and stable at high-temperature up to 125 °C. The glass transition temperature is above 180 °C, which is well above that of any conventional optical gelatins (about 80-90 °C). The polymer films prepared with the mixed solvent become much harder physically after poling. This implies that the organic solvent not only prevents chromosphere red from microscopic clustering but also helps the host and guest molecules to crosslink with each other completely.

To determine the waveguide propagation loss, three-layer planar waveguides were fabricated on a 4-inch silicon wafer for loss measurement. A 2-μm thick layer of pure gelatin (with refractive index of ~1.51) was first spin-coated as the lower cladding layer. Then a 4-μm thick layer of the gelatin polymer (with refractive index of 1.56) doped with the 30% ratio of chromosphere red to gelatin was spin-coated as the guiding layer. Finally a 2-μm thick layer of pure gelatin (with refractive index of ~1.51) was coated as the upper cladding layer. A planar EO waveguide was thus formed. The waveguide propagation was confirmed experimentally by observing a guided mode at the wavelength of 850 nm using a prism coupling technique. Fig. 2 is the photograph of the guided-wave propagation observed using a CCD camera. Multiple laser beams from linear laser diode array (at ~850 nm) were coupled into the planar waveguide through a prism coupler. The propagation loss was determined experimentally by measuring the integrated intensity distribution of the scattered light along the direction of propagation[18]. The measured loss was ~0.8 dB/cm at 850 nm for the EO waveguide and ~0.2 dB for pure gelatin waveguide. Fundamental mode was selected and coupled into the waveguide by prism coupling technique in all experiments.

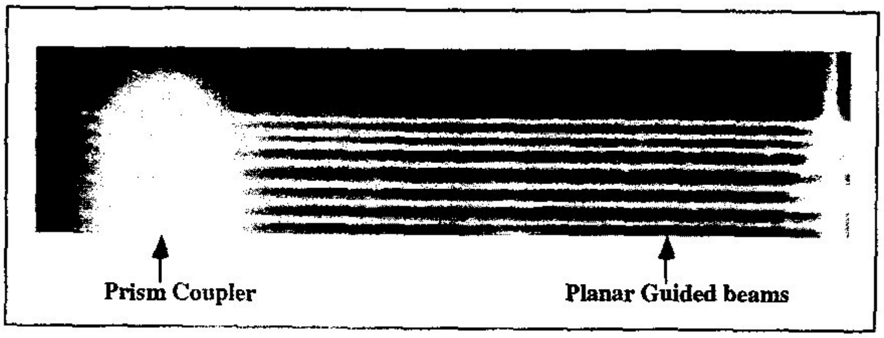

Fig. 2. Photograph of [illegible] beam propagation in an electro-optic planar waveguide at wavelength of 850 nm.

4. MULTIPLEXED WAVEGUIDE HOLOGRAMS IN POLYMER-BASED WAVEGUIDES

To obtain optical wavelength-selective switching, a multiplexed transmission waveguide hologram is required shown Fig. 3. The maximum number of holograms to be multiplexed is determined by the number of wavelengths in input beam. The number of holograms that can be multiplexed is limited by the maximum index modulation of photopolymer. The resolvable spots of electro-optic beam deflectors often limit the number of multiplexed holograms. Both electron-beam writing technique and holographic recording technique can be employed for fabricating such multiplexed holograms. In this reported demonstration, multiplexed holograms were recorded using a conventional two-beam interference technique. To construct a multiplexed waveguide hologram, multiple exposures are employed. The phase matching condition associated with each exposure can be easily designed theoretically and obtained experimentally[19].

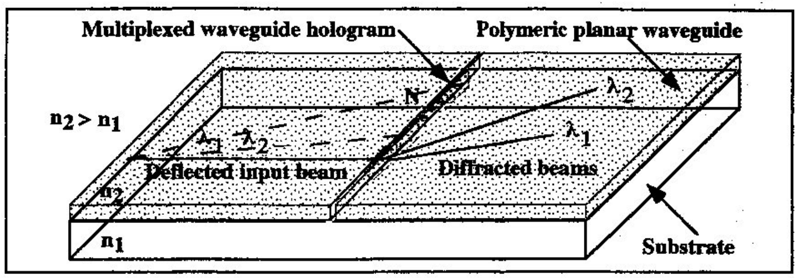

Fig. 3. Schematic of diagram of wavelength-division-multiplexing based on multiplexed waveguide holograms in a polymer-based planar waveguide.

For a fixed wavelength λ, the associated diffraction angle θ_j is given by[19]

$$\theta_j = 2\sin^{-1}(\lambda / 2N_{eff}\Lambda_j) \quad . \qquad (1)$$

Here Λ_j is the grating spacing and N_{eff} is the effective index of the polymer waveguide and λ is the operating wavelength. To precisely control the Bragg diffraction angle θ_j, N_{eff} has to be measured before hologram formation. Waveguide thickness and processing conditions have to be standardized to validate the design process. To fabricate a waveguide hologram with desired grating spacing, a well-collimated beam is introduced onto the waveguide emulsion containing the hologram. For each θ_j, two rotational angles φ_j and ω_j, which control the value of Λ_j and the diffraction angle θ_j, respectively, are selected for the waveguide hologram such that

$$\varphi_j = \cos^{-1}(\lambda_R / 2N_{eff}) \qquad (2)$$

and

$$\omega_j = 0.5\,(\pi - \theta_j) \qquad (3)$$

can be satisfied simultaneously. In Eq. (2), λ_R is the recording wavelength. For a perfectly phase-matched, lossless unslanted transmission grating, the diffraction efficiency can be written as

$$\eta_j = \sin^2\left(\frac{\pi \Delta n_j d}{\lambda_j \cos\theta_j}\xi\right), \qquad (4)$$

where Δn and d are the associated index modulation and the interaction length, respectively, and ξ is a constant which varies between 0 and 1 depending on the polarization of the incident beam. In Eq. (4), d is controlled by the lithographic process, and Δn is manipulated through exposure dosage and processing parameters. To provide high-efficiency diffraction, the required grating interaction length is

$$d = N\lambda \cos \theta_s / (2\Delta n) \ , \qquad (5)$$

where N is the number of multiplexed holograms. For typical parameters, N = 16, λ = 0.85 μm, Δn = 0.02, and θ_s = 15°, we calculate from Eq. (5) that the minimum grating interaction length is 330 μm. The high index modulation of holographic polymers allows us to fabricate highly multiplexed holograms on the same volume holographic emulsion using such a short interaction length.

For demonstration purpose, we multiplexed two holograms in a single planar waveguide, designed to operate at 850 nm with the diffraction angle (θ_j) of 34°, and at 860 nm with the diffraction angle of 44°, respectively. In the fabrication, each set of φ_j and ω_j was selected to record a waveguide hologram with the desired diffraction angle θ_j at a designed wavelength. The multiplexed waveguide hologram diffracted the incident beams into two output beams at wavelengths 850 nm and 860 nm, respectively. The interaction length of the multiplexed waveguide hologram was 0.5 mm. The waveguide thickness was 4 μm. We have successfully fabricated many types of multiplexed holograms in a polymer-based planar waveguide devices[13-15]. Up to 60 holograms can be recorded in the same emulsion area due to the large index modulation (up to 0.18) of dicromated gelatin (DCG), which is the photolime gel polymer doped with (~4% $(NH_4)_2Cr_2O_7$) ammonium dichromate[19]. Nearly 100% optical coupling efficiency can be achieved with a hologram interaction length about 0.5 mm[20].

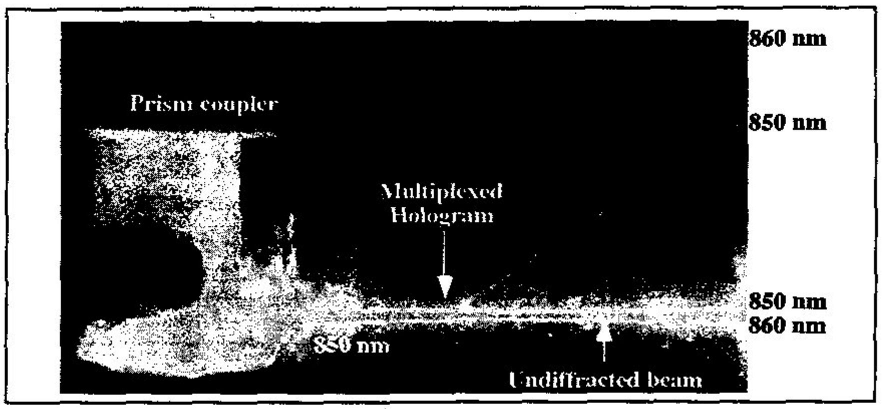

Fig. 4. Photograph of a multiplexed hologram with two diffracted output beams at 850 nm and 860 nm.

The hologram recording setup is shown in Fig. 5. An Ar^+ laser with an output power of 10 W is employed for recording holograms. The laser is operated in a single longitudinal mode for high temporal coherence. The output wavelength of 488 nm is selected due to the high photosensitivity of DCG at the wavelength of 460 nm region. A 3-dB beam splitter is used for creating the objective wave and reference beam. Microobjective lenses are used to expand the two laser beams into plane waves, followed by a spatial filter in its focal point. Two reflection mirrors, mounted on two three spatial and three angular microtranslation and rotation stages with resolution of 0.2 μm and 0.005° degree, are employed to control the recording beam directions. As the result, the incident angles (φ_j and ω_j) of the two recording beams can be well controlled during the recording. For better recording, an absorption plate is used and placed right behind the recording plate, where index-matching liquid is filled in the space between the two plates.

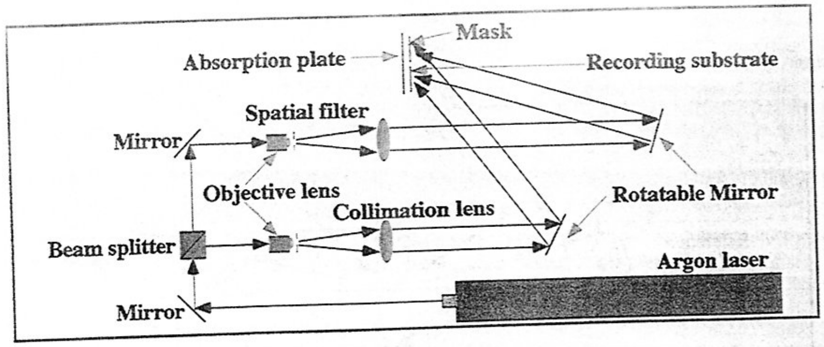

Fig. 5. Schematic diagram of the holographic recording setup.

5. Holographic Waveguide Lenses

The waveguide holographic lens that can diverge and/or converge the input light beam is another important buil block for the device shown in Fig. 1. Since both the multiplexed waveguide hologram and electro-optic prism array formed in a planar waveguide, a holographic waveguide lenses is highly desired in order to provide the lateral t confinement. For example, a holographic converging waveguide lens shown in Fig. 6 is useful to confine the incident t and focus it into output fibers. It should be noted that other types of waveguide lenses could also be used for an effe beam confinement and a high throughput coupling, including passive optical waveguide lenses, thermo-optic waveg lenses, and electro-optic waveguide lenses.

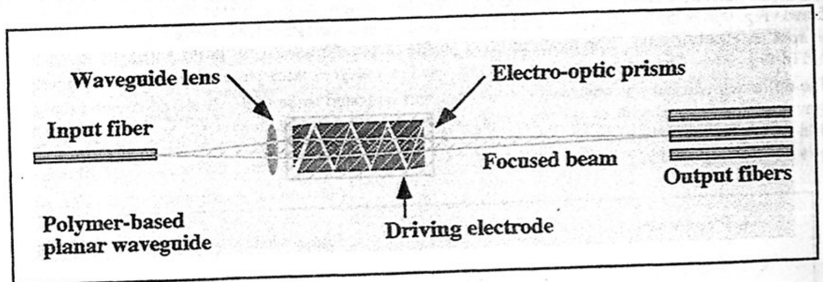

Fig. 6. Formation of a focused beam in a planar waveguide by using a waveguide holographic lens.

To construct the planar holographic waveguide lens, the recording and reconstruction phase matching condition i meridional plane is given by[13,22]

$$\sin(\theta_i) = \sin(\theta_c) - \frac{\lambda_c}{\lambda_o}\,[\sin(\theta_o) - \sin(\theta_r)] \tag{6}$$

and

$$\frac{1}{f_i} = \frac{1}{f_c} - \frac{\lambda_c}{\lambda_o}\left(\frac{1}{f_o} - \frac{1}{f_r}\right), \tag{7}$$

where f_q (q=c, i, o, r; defined in Fig. 7) is the distance between the corresponding point source and the center of the hologram, θ_q (q=c, I, o, r) is the respective off-axis angle as shown in Fig. 7. λ_c and λ_o represent the readout and recording wavelengths.

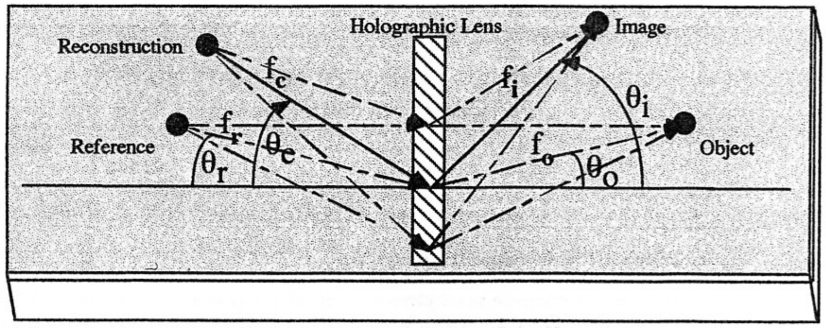

Fig. 7. Recording and readout geometry.

To fabricate the holographic waveguiude lens, a recording setup similar to Fig. 5 can be employed by adding a cylindrical lens in the reference arm. In case of a diverging waveguide beam, a cylindrical lens should be arranged as shown in Fig. 8(a). And in case of a converging waveguide beam, the problem is solved in an analogous manner as shown in Fig. 8(b). A key feature is that the focal line of the cylindrical lens is perpendicular to the waveguide plane and strikes it in the focal point S. We have fabricated a focusing lens in a planar waveguide by using dicromated gelatin spin-coated on GaAs substrate[23]. This polymeric material employed has a transmission bandwidth from 550 to 2800 nm, covering from visible to near infrared. Fig. 9(a) is the photograph of the fabricated holographic waveguide lens, where the planar guided beam and the focusing spot are clearly shown. The measured beam profile of the diffracted beam in the horizontal direction was further illustrated in Fig. 9(b). The holographic lens was fabricated in a 4-μm thick planar waveguide with a focal length of 30 mm. The diffraction efficiency at wavelength of 850 nm was measured to be 65%. It should be noted that the polymeric planar waveguide based on photolime gel was locally sensitized with an index modulation as high as 0.18. The fabricated holographic waveguide lens provides a mode-size matching between the incident beams and the output fibers, which determines the coupling efficiency.

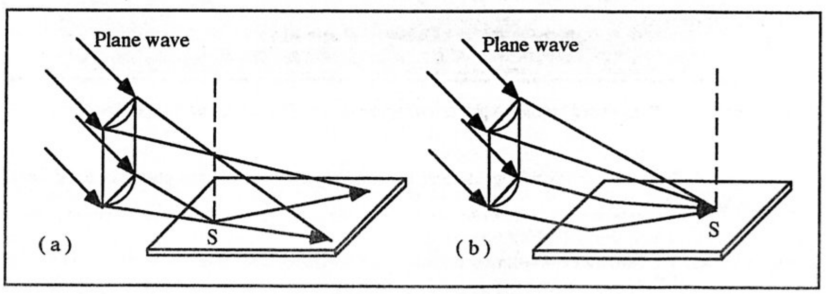

Fig. 8. Configuration for forming (a) a diverging lens and (b) a converging lens in planar waveguides.

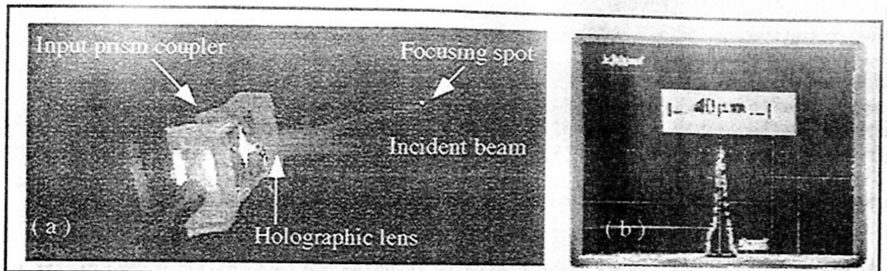

Fig. 9. (a) Observation of a polymer-based holographic lens on GaAs substrate. (b) Measure intensity distribution profiles in horizontal direction using a linear charged-coupled photodetector array.

6. ELECTRO-OPTIC WAVEGUIDE BEAM DEFLECTOR

The electro-optic beam deflector based on domain-inverted prisms in a polymer-based waveguide is a cornerstone for constructing the reconfigurable optical interconnect shown in Fig. 1. The number of resolvable spots N, which is directly related to the number of multiplexed holograms (N as shown in Fig. 3), is given by[24]

$$N = \frac{\pi \omega_0 n_0^3 \gamma L V}{\lambda h d} \tag{8}$$

where n_0 and γ are, respectively, the refractive index and electro-optic coefficient of the polymer, L is the length of the prism array, h is the height of the individual prism, λ is the free space wavelength and ω_0 is the beam waist. V is the applied voltage between the electrodes, and d_{eff} is the effective distance across which the voltage would be dropped to yield the actual field in the waveguide. Since some of the voltage will be dropped across the cladding layers, d_{eff} will be larger than the actual separation between the electrodes and is given by

$$d_{eff} = d_W + 2\left(\frac{\varepsilon_S}{\varepsilon_C}\right) d_C \ , \tag{9}$$

where d_W, d_C, ε_W, and ε_C, are the thickness and the permittivities of the waveguide and the cladding, respectively. Using $n_0 = 1.55$, $\gamma = 30 \times 10^{-12}$ m/V, $\lambda = 0.85$ μm, $\omega_0 = 10$ μm, (L/h) = 200, and $d_{eff} = 4$ μm, the number of resolvable spots N = 2/10V. The device performance can be improved by

(1) decreasing the height h of the prisms,

(2) increasing the length L,

(3) using a 2-D microprism array,

(4) increasing the electro-optic coefficient of polymer.

Fig. 10 shows the detailed schematic of the demonstrated device. The mounting substrate of this device was a typical silicon wafer. The three-layer planar waveguide was formed on top of the bottom electrode that was fabricated by the gold deposition of 240 nm. The two cladding layers had a refractive index of 1.53 and thickness of 1.0 μm. And the guiding layer had a refractive index of 1.62 and thickness of 2.2 μm. The high voltage alternated pulse-poling technique was employed for fabricating the domain-inverted prisms in electro-optic waveguides. Fig. 11 shows the schematic of the poling setup. Such a poling method allows us to fabricate precisely patterned domain-inverted prisms in polymeric waveguides. High electro-optic coefficient is also obtained due to the high electric poling field achievable (1000V/μm).

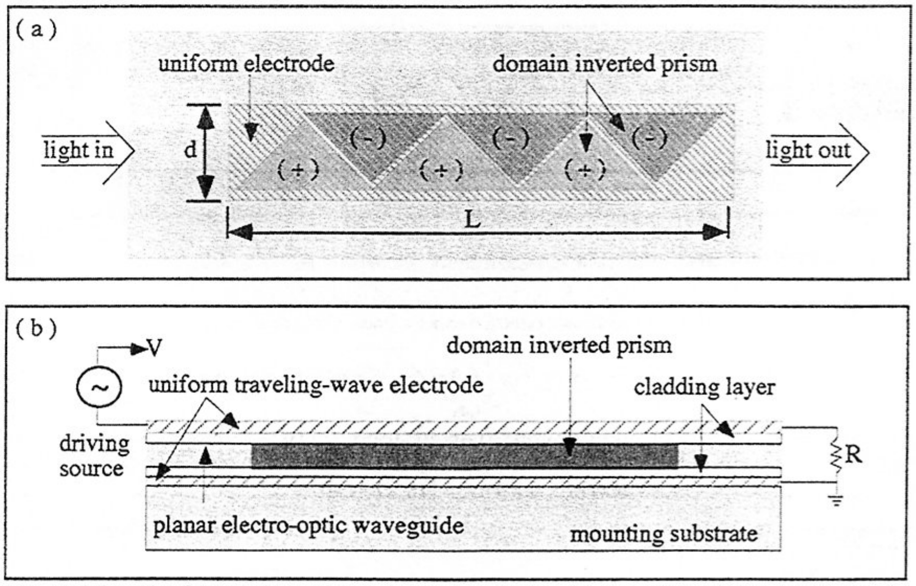

Fig. 10. Schematic of domain-inverted beam deflector fabricated: (a) Top view showing domain-inverted prisms; (b) Side view of the deflector with traveling wave electrode.

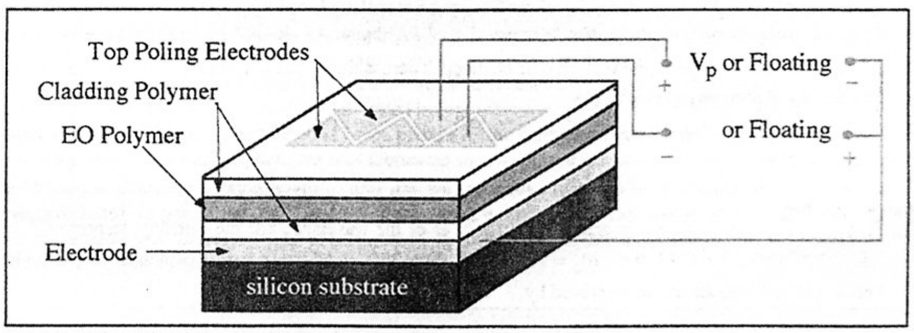

Fig. 11. Schematic of high voltage pulsed metal contact poling technique.

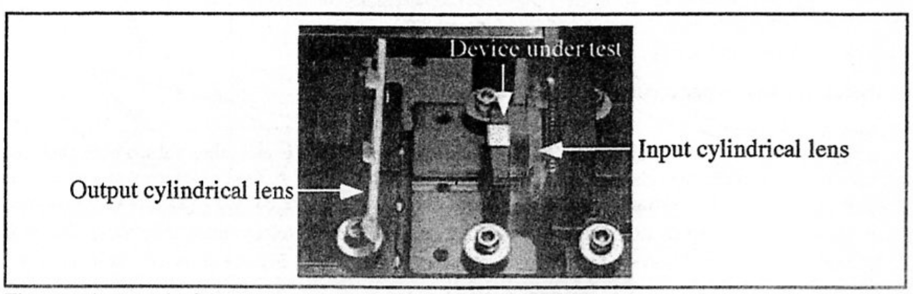

Fig. 12. Photograph of the beam-deflector test bed using two cylindrical lenses.

The test bed for the beam deflector is shown in Fig. 12. Beam deflection was demonstrated using a 685-nm diode laser from New Focus, which has a good Gaussian intensity profile. The laser was coupled into the planar waveguide of the beam deflector using a 1-cm focal-length lens, while a 2-cm focal-length lens was used at the output to collimate the output laser beam. The transmitted laser beam was incident upon the screen. A laser beam analyzer was placed to view the light scattered by the screen, so that a picture of the laser-beam spot formed on the screen was recorded. With the application of a drive voltage to the device, the beam propagation direction was changed in the plane of the planar waveguide.

The deflected-beam spots were recorded by a laser-beam analyzer as shown in Fig. 13 for various values of the applied voltage. The beam was deflected in the negative horizontal direction for negative values of the applied voltage and in the positive horizontal direction for positive values of the voltage, where the amount of deflection is symmetric with the applied voltage. In addition, Fig. 13 shows that essentially whole beam was deflected. There was no residual non-deflected beam. Thus the deflection efficiency was 100%. The fabricated device demonstrated the feasibility of the fabrication of laser beam deflector based on domain-inverted prisms in thin-film electro-optic polymers. The deflected laser beam maintained its Gaussian intensity profile after propagating and deflecting through the device.

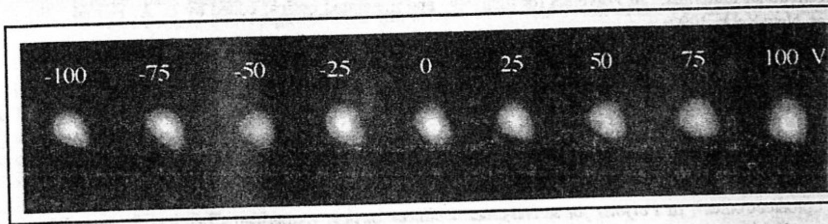

Fig. 13. Deflected laser beam profile in an observation screen for various values of drive voltages.

7. CONCLUDING REMARKS

We presented a concept of wavelength-selective switches based on a guide-wave electro-optic beam deflector i conjunction with multiplexed waveguide holograms for wavelength-division-multiplexing applications. The presente switching device functions as a fully transparent wavelength selective optical cross connect for fiber optic transmissic systems. We have demonstrated all building blocks required for constructing such a wavelength-selective optical switcl They are (1) the polymer-based electro-optic waveguide, (2) the waveguide lens, (3) the thin-film electro-optic prism array i polymeric waveguides and (4) the multiplexed waveguide holograms. The presented device is advantageous whenever there a need for low-power, high-speed, reliable, compact, low-loss, and reconfigurable optical cross connect systems using WDI techniques.

8. ACKNOWLEDGMENTS

This research is sponsored by BMDO, NASA, AFOSR, AFRL, ONR, Raychem Corp. and 3M Foundation.

9. REFERENCES

1. J. J. Pan, "Innovative photonic components technology for communication systems," *Proc. SPIE*, vol. 3949, 2000.
2. L. Y. Lin, E. L. Goldstein, and R. W. Tkach, "Free-space micromachined optical switches with sub-millisecond switching time for large-scale optical crossconnect," IEEE Photonics Technol. Lett., vol. 10, no. 4, pp. 525-527, 1998.
3. C. Gonzalez and S. D. Collins, "Micromachined 1xn fiber-optic switch," IEEE Photon. Technol. Lett., vol. 9, no. 5, pp. 616-618, 1997.
4. R. G. Lindquist, J. H. Kulick, G. P. Nordin, J. M. Jarem, S. T. Kowel, and M. Friends, "High-resolution liquid-crystal phase grating formed by fringing fields from interdigitated electrodes," Opt. Lett., vol. 19, no. 9, pp. 670-672, 1994.
5. Liu, Jian-Yu ; Wu, Kuang-Yi, "Digital programmable wavelength-switching technology,": LEOS Summer Topical Meeting Proceedings of the 1997 LEOS Summer Topical Meeting Aug. pp. 11-15, 1997.
6. R. C. Alferness, "Waveguide electrooptic switch arrays," IEEE J. of Selected Areas in Communications, vol. 6, pp. 1117-1130, 1988.
7. R. A. Norwood, T. Findakly, H. A. Goldberg, G. Khanarian, J. B. Stamatoff, and H. N. Yoon, "Optical polymers and multifunctional materials," in Polymers for lightwave and integrated optics, edited by L. A. Hornak, 287-320 (Marcel Dekker, New York, 1992).
8. T. C. Kowalczyk, T.Z. Kosc, K.D. Singer, A.J. Beuhler, D.A. Wargoski, P.A. Cahill, C.H. Seager, and M.B. Meihardt, "Crosslinked polyimide electro-optic materials," J. Appl. Phys., vol. 78, p. 5876, 1995.
9. E.M. Cross, K.M. White, R.S. Moshrefzadeh, C.V. Francis, "Azobenzeimidazole compounds and polymers for nonlinear optics", Macromolecules, vol. **28**, p. 2526, 1995.
10. C. Xu, B. Wu, O. Todorava, L. Dalton, Y. Shi, P. M. Ranon, and W.H. Steier, "Stabilization of dipole alignment of poled nonlinear optical polymers by ultrastructure synthesis", Macromolecules, vol. 26, p. 5303, 1993.
11. R. Levenson, J. Liang, C. Rossier, R. Hierle, E. Taussaere, N. Bouadma and J. Zyss, Advances in organic polymer-based optoelectronics", in *Polymer for second-order nonlinear optics,* (American Chemical Society, Washington, DC, 1995), p. 436.
12. G.F. Lipscomb, R. S. Lytel, A.J. Tickmnor, T. E. Van Eck, S. L. Kwinatwowski, and D.G. Girton, "Developments in organic electro-optic devices at Lockheed", *Proc. SPIE*, vol. 1337, p. 23-33, 1990.
13. Suning Tang, Ting Li, Feiming Li, Charles Zhou, and Ray T. Chen, "A holographic waveguide microlens array for surface normal optical interconnects," IEEE Photon. Technol. Lett., vol. 8, no. 11, pp. 1498-1500, 1996.
14. Suning Tang, Rob Mayer, Maggie M. Li, Luke Graham, and Ray T. Chen, "A novel wavelength-division-demultiplexer with optical in-plane to surface-normal conversion," IEEE Photon. Technol. Lett., vol. 7, no. 8, pp. 908-910, 1995.
15. Suning Tang, Ray T. Chen, Bulang Li, and James Foshee, "Polymeric waveguide circuits for airborne photonic phased-array-antennas enable communication without boundaries," IEEE Circuits & Devices, vol. 16, no. 1, pp. 10-16, 2000.
16. T. C. Lubensky and P. A. Pincus, Phys. Today, p. 44, Oct. 1984.
17. K. D. Singer, S. L. Lalama, J. E. Sohn and R. D. Small, "Electro-optic Organic Materials", Nonlinear Optical Properties of Organic Molecules and Crystals, D. S. Chemla and J. Zyss, Eds., Academic Press, Orlando, 1, pp. 437-468, 1987.
18. Linghui Wu, Feiming Li, Suning Tang, Bipin Bihari and Ray T. Chen, "Compression-molded three dimensional tapered polymeric waveguides for low-loss optoelectronic packaging," IEEE Photon. Technol. Lett., vol. 9, no. 2, pp. 1601-1603, 1997.
19. Ray. T. Chen, Michael R. Wang, and Tomasz Jannson, "Intraplane guided wave massive fanout optical interconnections," Appl. Phys. Lett., vol. 57, pp. 2071-2073, 1990.
20. Ray T. Chen, "Near infrared 12-channel wavelength division demulpiplexer on a semi-insulating GaAs substrate," 1993 OSA Topical Meeting on Integrated Photonic Research, IME-3, pp. 18-21, 1993.
21. Ray T. Chen, "Holographic elements fanout laser beams," Laser Focus World, pp. 221-230, June 1996.
22. Y. Amitai, A. A. Friesem and V. Weiss, "Designing holographic lenses with different recording and readout wavelengths," J. Opt. Soc. Am. A 7, No. 1, pp. 80-86, 1990.
23. Ray T. Chen, "Graded-index polymer-based waveguide lens working at visible wavelengths on GaAs substrate for optoelectronic interconnects," Appl. Phys. Lett., vol. 62, no. 20, pp. 2495-2497, 1993.
24. J. Li, H. C. Cheng, M. J. Kawas, D. N. Lamneth, T. E. Schlesinger, and D. D. Stancil, "Electrooptic wafer beam deflector in LiTaO3," Photon. Technol. Lett., vol. 8, no. 11, pp. 1486-1488, 1996.