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An integrated thin-film thermo-optic waveguide beam deflector

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We have demonstrated the operation of a thin-film thermo-optical beam deflector in a three-layer optical planar waveguide. The fabricated waveguide beam deflector consists of a thin-film SiO_2 bottom cladding layer, a thin-film polymer top cladding layer, and alternatively positioned thin-film polymer and silica microprisms as the guiding layer. The beam deflection is achieved through the thermo-optic effect that results in opposed index changes in polymer and silica with respect to temperature changes. The measured deflection sensitivity is 0.06°/°C, for the fabricated device with a 7.0 mm interaction length at the wavelength of 632.8 nm. © *2000 American Institute of Physics.* [S0003-6951(00)00916-5]

Nonmechanical beam deflectors are of interest for many military and commercial applications such as laser tracking and targeting, optical data storage, optical switching, laser printing, scanning, optical sensing, optical computing, and laser control. Current beam steering systems are very complex, costly, and too large for most airborne/space applications. Devices for controlling the direction of a laser beam have been limited in the past, and restricted almost entirely to such methods as galvanic mirror, and acousto-optic and electro-optic beam deflection. These methods suffer from various problems including, high driving power, limited speed, low resolution, and complex fabrication. The most promising technology to date for scanning a laser beam without any moving parts is electro-optical beam deflection. Several device concepts for electro-optic deflectors have been reported in the literature.[1–7] Electro-optic beam deflectors using domain reversal in ferroelectric crystals have also been demonstrated. However, the major drawback of this method is the demand of very high driving voltages (>1000 V).[8]

The thermo-optic beam effect in optical thin-film waveguides presents an attractive alternative for fabricating low power optical beam deflectors with large scanning angles. At present, polymers and silica are the most reliable optical waveguide materials for thermo-optic applications. Optical silica thin films are derived from the well-established silica-on-silicon technology for passive waveguide components, whereas optical polymeric thin films are primarily developed for optoelectronic interconnect applications.[9–14]

Optical polymers show large thermo-optic coefficients in combination with low thermal conductivities resulting in low electrical power consumption for thermo-optic beam scanning. The rise in temperature of the heating electrode is proportional to the dissipated electrical power density and inversely proportional to the thermal conductivity, σ, of the waveguide material. For optical polymers, σ is about 0.05–0.2 W/mK, while for silica σ is about 1.4 W/mK. Therefore, to induce the same temperature difference in thin-film waveguides, it takes at least seven times more power for silica-on-silicon waveguides than for a polymeric waveguides. In addition, the thermo-optic coefficient of polymers ($-1.4\times10^{-4}/°C$) is an order of magnitude larger than that of silica ($+1\times10^{-5}/°C$). It should be noted that polymer and silica have oppositely signed thermo-optic coefficients. As a result, it takes about two orders of magnitude less power to induce the same absolute difference in effective indices in polymeric waveguides than in silica waveguides. More importantly, because of the hybrid nature of polymer technology, it opens up the possibility for large-scale integration of optical devices on many substrates.

In this letter, we present a novel device concept for fabricating an integrated thin-film optical waveguide beam deflector based on the thermo-optic effect. The thin-film waveguide beam deflector consists of a SiO_2 bottom cladding layer, a polymer top cladding layer, and a guiding layer of alternatively positioned thin-film polymeric and silica microprisms. The polymeric and silica microprisms are alternatively cascaded in a two-dimensional array pattern. The beam deflection is achieved through the thermo-optic effect in both polymer and silica. Such a novel device concept takes advantage of the opposite thermo-optic responses between the optical polymers and optical glasses, which results in an opposed index modulation with respect to temperature change.

Figure 1 shows the schematic diagram of the demon-

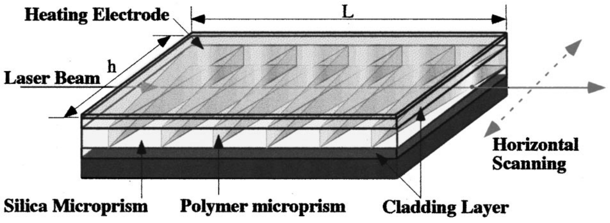

FIG. 1. Schematic diagram of a thin-film waveguide beam deflector based on thermo-optic microprisms.

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strated thermo-optic waveguide beam deflector. The unique feature of the device is that triangular waveguide prisms are made out of alternatively combined polymer and silica in a three layer planar waveguide. The localized heating in the prism region is obtained by using a thin-film chromium heating electrode on top of the planar waveguide. The beam deflection is achieved through the thermo-optic effect in both the polymer and silica microprisms, which results in opposite index changes with respect to temperature changes. The low driving power is realized by employing cascaded thermo-optic microprisms, which enhance the deflection angle by continuously adding up the deflections for a fixed temperature change. As shown in Fig. 1, the multilayer device structure is composed of a guiding layer, an upper cladding layer (polymer), a bottom cladding layer (SiO_2), a heating electrode layer (chromium), and a silicon substrate for mechanical support and heat sinking. The guiding layer composed of alternatively arranged microprisms made by GeO_2-doped silica and optical polymer. As a result, the guiding layer is composed of both polymer and silica which respectively have negative and positive thermo-optic coefficients. The GeO_2-doped silica and optical polymer are engineered to have the same refractive index at 20 °C. The upper cladding layer is needed between the waveguide layer and chromium heating electrode to reduce the optical absorption by the electrode due to the evanescent field of the optical mode.

With a change in temperature, the refractive indices in polymer and in silica change in opposite directions, resulting in an index difference between the polymer and silica regions. Most optical polymers have a thermo-optic coefficient on the order of $-10^{-4}/\,°\mathrm{C}$, and silica thin films have a thermo-optic coefficient in the order of in the order of $10^{-5}/\,°\mathrm{C}$. As the thermo-optic response is a linear function of temperature change, the index change is given by

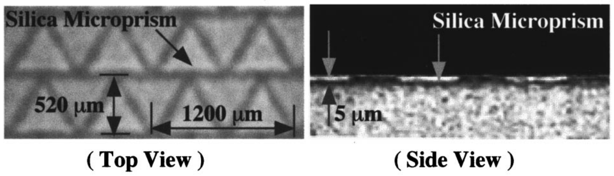
$$\Delta n = \frac{dn}{dT}\Delta T. \tag{1}$$

This thermo-optic index change will result in a deflection angle of θ[8]

$$\theta = (\Delta n)\frac{L}{n} = (|\Delta n_{(\mathrm{polymer})}| + |\Delta n_{(\mathrm{silica})}|)\frac{L}{h}, \tag{2}$$

where L is the total length of the prism array and h is the height of the prism as indicated in Fig. 1. The temperature change will produce an index change in both the polymer and silica regions, which constructively contribute to the total index change in the prism arrays. Assuming a polymer thermo-optic coefficient of $-7\times10^{-5}/\,°\mathrm{C}$, a silica thermo-optic coefficient of $1\times10^{-5}/\,°\mathrm{C}$, a length of $L=7.0\,\mathrm{mm}$, and a height of $h=520\,\mu\mathrm{m}$, the deflection sensitivity calculated form Eq. (1) and Eq. (2) is $d\theta/dT=0.06°/°\mathrm{C}$.

The demonstrated thin-film thermo-optic waveguide beam deflector is fabricated using optical polymer and GeO_2 doped silica waveguide. The starting silica thin-film planar waveguide has a cladding layer of a thickness of 15 μm and a guiding layer of a thickness of 5 μm, prefabricated on a silicon wafer. The fabrication process started with the reactive ion etching (RIE) of a silica-on-silicon planar waveguide wafer for fabricating microprism structures with 600 μm equilateral triangles in the guiding layer. The resulting prism cavities in the guiding layer are spun coat with an optical crosslinking polymer that is engineered to have the same refractive index as that of the waveguide core layer at room temperature, an index of 1.464. The polymer-coated wafer is then polished and examined with a microscope inspection system to ensure that the core layer (now composed of both polymer and doped silica) thickness is 5 μm. The wafer is further spun coat with an upper cladding polymer layer that has an index of 1.420 and thickness of 5 μm. The fabricated device has an interaction length of 7 mm.



(Top View) (Side View)

FIG. 2. Microscope photograph of fabricated microprisms.

Low loss cross-linked polyacrylates are selected for fabrication of waveguide guiding and cladding layer, with optical refractive indices of 1.464 and 1.420, respectively. These polymers have a glass transition temperature T_g of 60 °C and are thermally stable up to 250 °C after cross linking. The optical loss of the polymers is determined to be 0.2 dB/cm at 633 nm and 0.3 dB/cm at 1550 nm. The spin-coated optical polymers are cross linked by the ultraviolet exposure under the EFO Sultracure 100ss Plus Lamp for 40 min. The optical characteristics are evaluated with the Metricon 2010 Prism Coupler System for optical loss and index measurements. Figure 2 shows microscope photograph of the microprisms in the guiding layer formed by the reactive ion etching technique.

The experimental setup for testing the thermo-optic deflector is illustrated in Fig. 3. A He–Ne laser (632.8 nm) was employed as the light source. The laser beam was coupled into the polymeric waveguide through free space end-fire coupling using a spherical lens with a focal length of 50 mm and a cylindrical gradient index rod lens with a focal length of 2.1 mm. The output beam was collimated with another cylindrical gradient index rod lens with a focal length of 1.7 mm. The focal lengths of the lenses were chosen and optimized based on the ray tracing technique. The input beam was designed to have a dimension of $70\,\mu\mathrm{m}\times5\,\mu\mathrm{m}$ at the entrance of the waveguide. This beam size was compatible with the fabricated prism array with an effective width of 520 μm and a thickness of 5 μm. The relatively large beam

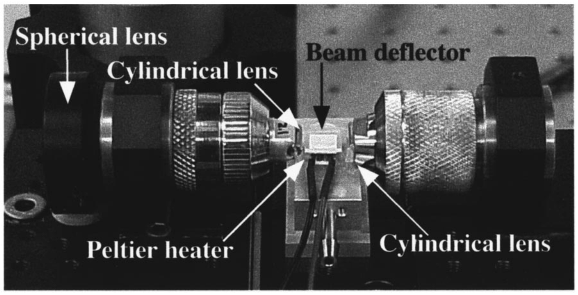


FIG. 3. Photograph of experimental setup for demonstrating thermo-optic beam deflection.

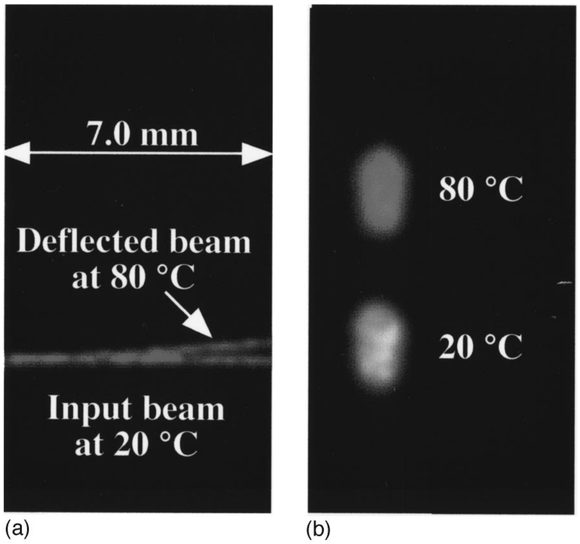


FIG. 4. Photograph of (a) the transmitted beam at 20 °C and the thermo-optically deflected beam at 80 °C, and (b) the associated far field beam profiles.

width (70 μm) was used for its low divergence, resulting in a larger number of resolvable spots.[8]

We have observed beam deflection in a thin-film thermo-optic waveguide beam deflector. The initial test was conducted with the sample heated by a Peltier device from underneath instead of using the fabricated heating electrodes. The electrical power needed to increase the device temperature by 60° is about 100 mW. At this temperature change, a beam deflection of about 3.7° was achieved as shown in Fig. 4. Based on the observed beam deflection angle, we estimated that the thermo-optical coefficient of the polymer used is $dn/dT = -7\times10^{-5}$. With the Peltier heater configuration, the heating efficiency is low due to the large thickness (500 μm) of the silicon substrate. If the heating were conducted through top heating electrodes, an increase of efficiency and a decrease of electrical power consumption by a factor of ten could be expected, allowing the device to be operated with power consumption less than 10 mW.

We have demonstrated in a thermo-optical beam deflector based on thin-film microprisms in a three-layer optical planar waveguide. A temperature increase of 60 °C, corresponding to 100 mW power consumption with the Peltier heating configuration has produced a beam deflection angle of 3.7°. The geometry and fabrication steps for such thin-film waveguide beam deflectors are compatible with advanced thin-film technologies for future low-cost fabrication. Based on the beam deflection angle observed, we estimated that the thermo-optical coefficient of the polymer used is $dn/dT = -7\times10^{-5}$. Under a temperature change of 60 °C, the number of multiple resolvable spots is estimated to be six in theory. In our experimental observation, the number of resolvable spots appeared to be three instead of six. This might be due to the fact that the actual Gaussian beam waist is a factor of two smaller than the 70 μm beam size employed. Further improvements on device performance can be achieved by selecting optical polymers with higher thermo-optic coefficients, employing a longer device length, and using the more efficient chromium heating electrodes. The demonstrated thin-film waveguide beam deflector could find wide application in laser beam steering, optical storage, and optical communications systems.

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