supported by our inability to measure any two-photon absorption before reaching the damage-threshold input intensity.

There are two figures of merit used to assess the suitability of a nonlinear material for all-optical switching devices [8]. If the loss is dominated by linear absorption, $W = \Delta n/\alpha\lambda$ must be larger than unity. In PTS, $W > 1$ for $I > 20\text{MW/cm}^2$, based on attenuation coefficients estimated from those reported by Thakur, Frye and Greene [9]. In the case where two-photon absorption dominates the loss, we need $T = 2\alpha_2\lambda|n_2|$ to be less than unity. For PTS, the value of this parameter may vary with both intensity and pulse width. For the value of the nonlinear refractive index and the upper limit of the two-photon absorption coefficient reported in this Letter, the T-parameter has a maximum value of 0.04, but may, in fact, approach 0. It has been previously shown that, with increasing T, the switching power increases and the switching tends to become incomplete in a nonlinear directional coupler [10]. With as small a T parameter as given here, we conclude that PTS is highly suitable for all optical applications at 1600nm. Furthermore, by extrapolating from measurements performed at 1580nm we find that the T-parameter is less than unity for at least part of the gain bandwidth of erbium-doped fibre amplifiers [7].

In conclusion, we have measured the complex nonlinear refractive index of PTS at 1600nm. The nonlinear refractive index n_2 was found to vary linearly with intensity. The two-photon absorption coefficient could not be measured before the damage threshold was reached, which resulted in our ability only to establish an upper limit for α_2. At this wavelength, the values of the complex nonlinear refractive index, through the figures of merit, indicate that PTS is a good candidate for all-optical switching, and has potential for use in telecommunications.

Acknowledgment: The CREOL research was supported by AFOSR (91-0339).

17 January 1994
Electronics Letters Online No: 19940285

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Three-dimensional micro-Fresnel optical elements fabricated by micromachining technique

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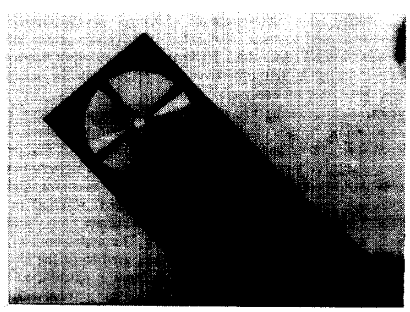
Indexing terms: Lenses, Optical elements, Nanotechnology

The authors report, for the first time, a three-dimensional binary phase micro-Fresnel optical element standing perpendicular to the substrate. The optical element is fabricated by a micromachining technique. The element has a diameter of 650µm, a focal length of 0.5mm and an optical axis of 1mm above the surface of the substrate. Light from an optical fibre is successfully collimated by the micro-optical element, and the beam profile closely approximates a Gaussian shape.

Micro-Fresnel optical elements are important components for micro-optics. They can be made of thin films and can achieve small focal lengths, making them attractive for integration with other optical devices. Both blazed and binary micro-Fresnel optical elements have been studied and fabricated [1, 2]. These diffractive optical elements have the potential for mass production because of their simplicity of design and fabrication. To date, however, most of the Fresnel optical elements reported are fabricated with their element plates lying on the surface of the substrate, which limits the flexibility to integrate them with other optoelectronic components.

In this Letter, we report a three-dimensional binary phase micro-Fresnel optical element which stands perpendicular to the substrate. The micro-Fresnel element consists of a Fresnel zone plate and integrated micromachined hinges and spring latches, all made of polysilicon [3]. With the microhinge structures, the element can be rotated out of the substrate freely, and firmly locked by the microspring latches. The length of the spring latches determines the angle between the element and the substrate. With a similar micromachining technique, we can also make three-dimensional micromirrors, micro-beamsplitters and microgratings standing on the substrate with any specified angle. These structures can be combined with micromotors [4] and constitute the basic components of free-space micro-optics. We can then build a 'micro-optical system' on a silicon wafer, make micro-optical devices such as Fabry-Perot etalons, or use it to link optoelectronic devices such as semiconductor lasers, isolators, optical fibres, and photodetectors.



[5647]

Fig. 1 *Photograph of three-dimensional micro-Fresnel optical element with diameter of 650µm*

White dots are etch holes to speed release etch

The fabrication process of the micro-Fresnel optical element is described in the following. A phosphosilicate glass (PSG) of 2μm thickness is deposited first on the silicon substrate as a sacrificial layer. Part of the microhinges and spring latch structures are defined on the first 2μm-thick polysilicon layer. A second PSG layer of 0.5μm thickness is grown on the polysilicon layer. After making the contact holes through the PSG for mechanical support, a second 1.5μm-thick polysilicon layer is deposited. The Fresnel pattern, hinges and spring latches are defined by lithography and etched through the second polysilicon layer. After selectively removing the PSG by HF, the Fresnel zone plate is rotated out of the plane of the wafer with its bottom fixed on the substrate by the microhinges. The plates are firmly locked by the microspring latches. The fabrication process was done at the Microelectronic Center in North Carolina (MCNC), and the thickness of the Fresnel zone plate is 1.5μm. Fig. 1 shows the photograph of the three-dimensional Fresnel element after assembly. The shadow below the actual optical element is the mirror image of the optical element reflected from the silicon surface. The optical element has a diameter of 650μm, a primary focal length of 0.5mm, and an optical axis of 1mm above the Si surface. A 50nm-thick Au layer is coated on the optical element surface to completely block light transmission through the dark zones.

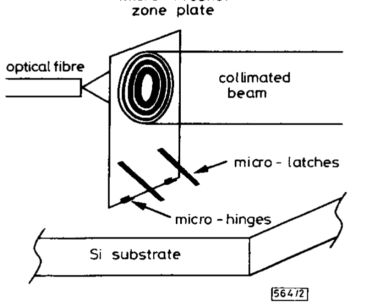


Fig. 2 *Schematic diagram of fibre coupling experiment using micro-Fresnel optical element*

Optical axis is 1mm above Si surface

The micro-Fresnel optical element is used to collimate a diverging optical beam from an optical fibre at λ = 980nm, as shown in Fig. 2. The fibre is parallel to the substrate. The tip of the fibre is positioned at 0.5mm from the optical element, which is the focal length of the element. The full-width-at-half-maximum (FWHM) of the beam, with and without passing through the element, against the distance from the optical element is shown in Fig. 3

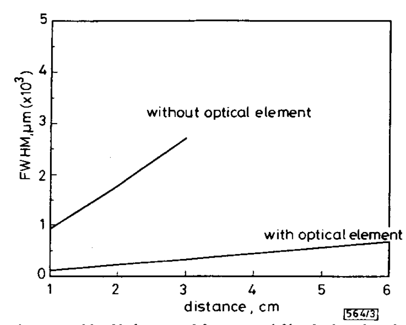


Fig. 3 *Beamwidth of light emitted from optical fibre both with and without the light passing through the optical element as a function of distance from optical element*

(measured by a Mechantek beamscope). Without the Fresnel element, the beam diverges too much beyond 30mm such that its beam profile cannot be measured accurately by the beamscope. The beam diverges at an angle of 2.6° in the absence of the optical element. It is collimated to 0.33° by the micro-Fresnel element. The binary phase Fresnel element is chosen for our first demonstration because of its simplicity. Other components can be made using similar methods. The deviation from the exact phase modulation (the thickness of the optical element is a second-order polynomial function of the distance from the centre with 2π phase modulus) reduces the diffraction efficiency and the focusing ability of the optical element. This explains the slight divergence of the collimated beam. A binary phase Fresnel optical element has multiple focal points with the focal length of the nth focal point equal to $1/n^2$ of the first one. To those secondary focal points, the light is not collimated when the light source is placed at the primary focal point. The three dimensional profile of the collimated beam at a distance of 1cm from the optical element is shown in Fig. 4. The beam shape is fit by the Gaussian profile to 95%.

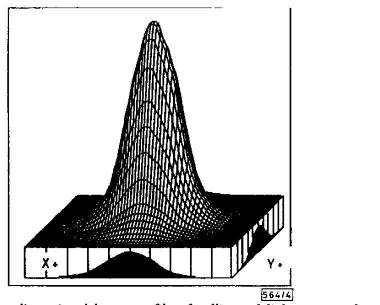


Fig. 4 *Three-dimensional beam profile of collimated light measured at distance of 1cm from optical element*

In summary, a three-dimensional micro-Fresnel optical element standing perpendicular to the substrate has been demonstrated for the first time using micromachining technology. Light emitted from an optical fibre is successfully collimated by the micro-Fresnel optical element. These optical elements can be combined with other three-dimensional micro-optical components on a silicon substrate to form a free-space micro-optical bench. The micro-optical bench can also include active optical components such as diode lasers and photodetectors to form micro-optical systems.

4 January 1994
Electronics Letters Online No: 19940277

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