Graded-index polymer-based waveguide lens working at visible wavelengths on GaAs substrate for optoelectronic interconnects

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A polymer-based graded index (GRIN with $n=1.4$–1.6) waveguide lens was demonstrated on a semi-insulating GaAs substrate. The transparent bandwidth of the polymer film (photolime gel) is from ~280 to ~2800 nm. Therefore, UV (ultraviolet), visible and near-IR (infrared) light can be employed as the signal carrier wavelength. In this letter, an off-axis chirped grating lens working at 632.8 nm with 35 mm focal length, 680/mm chirp rate, and angular field of view of 6° was demonstrated. Measured focal spot size of the main lobe is 5.6 μm which is very close to the theoretical prediction (4.2 μm). The crosslink-induced index modulation is as high as 0.2. Therefore, an array of chirped phase grating lenses can be multiplexed onto the same holographic emulsion for one- and two-dimensional massive fanout optical interconnects and signal processing.

Realization of an integrated optic circuit for optoelectronic interconnects and signal processing applications requires a myriad of guided wave devices such a planar and channel waveguides, gratings, lenses, and electro-optic modulators,[1–3] etc. To date, integrated optical circuits (IOCs) have been demonstrated on GaAs, $LiNbO_3$, and glass substrates to perform various optical signal processing and computing functions. These IOCs fabrication technologies, however, are substrate dependent and thus subject to material system selection. A substrate-independent device fabrication method is required to provide a transferable guided wave device technology for system integration. For example, board-to-board and module-to-module optoelectronic interconnects may involve substrate materials such as glass, Al_2O_3, Si, BeO, etc. To implement guided wave optical interconnects in these interconnection hierarchies requires a universal waveguide fabrication method suitable for all these substrates. One of the most important motivations of conducting polymer-based photonic device research is to provide such building blocks.

We have recently demonstrated a graded index (GRIN) polymer with a transparent bandwidth from ~280 to ~2800 nm. The GRIN property makes the polymer an excellent guiding medium (loss <0.1 dB/cm at 1.31 μm)[4] on an array of substrates regardless of their indices of refraction and conductivities.[5–7] Formation of planar waveguides, channel waveguides,[4,8] single and multiplexed waveguide holograms,[9] current injection collinear asymmetrical waveguide modulators,[10] electro-optic modulators with γ_{33} equivalent to that of $LiNbO_3$,[11] and polymer waveguide amplifier[12] were previously reported, based on the same polymeric material.

In this letter, we report the formation of a graded index (GRIN, $n=1.4$–1.6) single-mode polymer waveguide lens on a semi-insulating GaAs substrate. The physical dimension of the waveguide lens is defined by the predesigned mask pattern. The photo-lime gel we used is extracted from animal tissue. When dried, this biophotopolymer is a rigid glass film that shows very little absorption or optical scattering. It is soluble in aqueous solutions and insoluble in most organic solvents such as benzene, acetone, petroleum ether, and absolute alcohol. As a result of this, negative photoresist was used as a masking layer for emulsion sensitization. The recording of the chirp grating lens can be realized either by mask contact printing or by holographic recording. In the reported demonstration, the waveguide lens was recorded holographically using the geometry suggested by Ref. 13. A schematic showing the reconstructed waveguide lens is included in Fig. 1. This figure shows the reconstruction of the chirped grating lens. The incident guided beam is diffracted by the chirped grating lens at angles in the range of θ_l–θ_h. For the off-axis chirped grating lens shown in Fig. 1, the incident beam cannot be at the Bragg angle across the entire aperture, L of the lens. It is easy to show that

$$\theta_l=\cot^{-1}\left(\frac{\cos\theta_i}{\sin\theta_i-\dfrac{\lambda}{\Lambda_l\cdot \mathrm{N_{eff}}}}\right) \quad (1)$$

and

$$\theta_h=\cot^{-1}\left(\frac{\cos\theta_i}{\sin\theta_i-\dfrac{\lambda}{\Lambda_h\cdot \mathrm{N_{eff}}}}\right) \quad (2)$$

where θ_i, θ_l, and θ_h are defined in Fig. 1, λ is the optical wavelength, $\mathrm{N_{eff}}$ is the effective index of the waveguide mode and $^{1/\Lambda}l$ and $^{1/\Lambda}h$ are the grating spatial frequency of the chirped grating at the indicated locations. The diffracted beam coming out of the grating region will thus cross at a distance f, which is defined as the focal length of the chirped grating lens and is determined geometrically by

$$f=\frac{L}{\tan\theta_h-\tan\theta_\ell} \quad (3)$$

where L is the lens aperture. It is clear from Eqs. (1)–(3) that the focal length of guided wave chirped grating lens is controlled by the chirp rate $(1/\Lambda_h)-(1/\Lambda_l)/L$ and the effective wavelength, i.e., $^{1/N}$eff of the waveguide. Chirp rate of 680/mm is demonstrated in our case. A higher chirp rate can be realized by using a fast cylindrical lens of recording.[13] Figure 2 illustrates a section of the polymer-

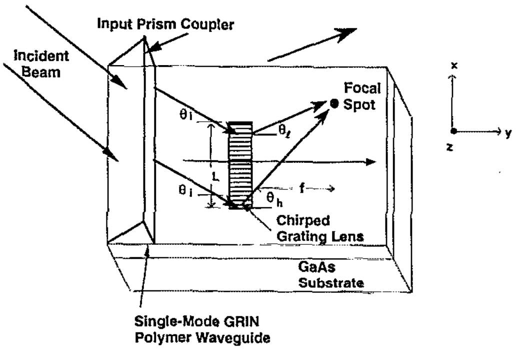


FIG. 1. Schematic of the single-mode graded index polymer waveguide lens on a GaAs substrate.

based chirped grating lens. The linear pattern shown in Fig. 2 is a phase grating pattern rather than a surface relief pattern. The depth of the phase grating (z direction of Fig. 1) is equivalent to that of the polymer waveguide. As a result, the diffraction efficiency derived from coupled mode theory[14] is stronger than for a surface relief grating structure with a partial overlap.[15] The formation of a phase grating structure also reduces scattering when compared with a surface-relief structure because of the existence of the surface corrugation caused by etching processes such as chemical etching and ion milling.

The polymeric material we employed has a transmission bandwidth from 280 to 2800 nm,[7] which covers UV, visible, and near-infrared optical wavelengths. A polymer-based chirped grating lens working in the UV and visible spectra can thus be realized in the GaAs substrate. A GRIN polymer waveguide lens working at a wavelength of

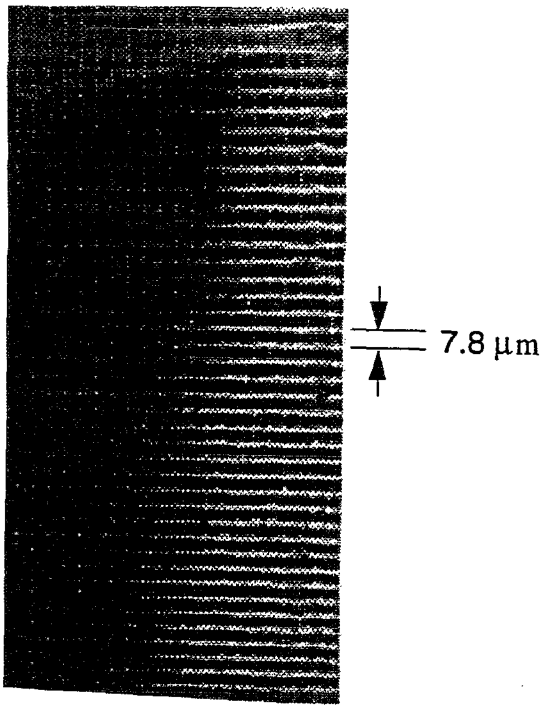


FIG. 2. A portion of the polymer-based chirp grating on GaAs substrate.

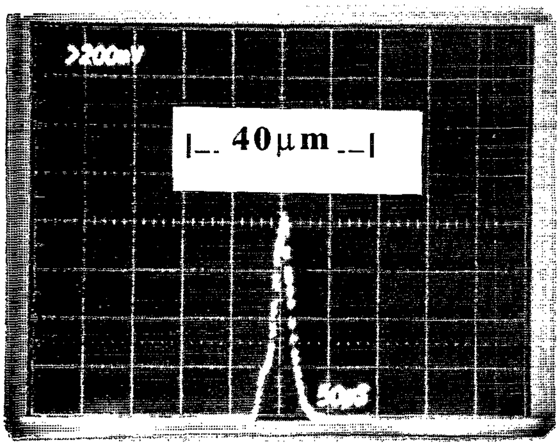
FIG. 3. Observation of a polymer-based chirped grating lens on GaAs working at 632.8 nm. The equivalent micro-optical components in this photograph are illustrated in Fig. 1.

632.8 nm is shown in Fig. 3 where a guiding layer and focusing lens are clearly shown. Demonstration of a waveguide lens at other visible wavelengths was also conducted and the results are not presented in this letter. The performance feature and the design parameters for this waveguide lens are summarized in Table I. The range of index tuning is around 1.4–1.6. The output end face of the device was further cleaved to facilitate near-field imaging. The focal spot profiles of the main lobe of the diffracted beam in both the horizontal and vertical directions are further illustrated in Fig. 4. These profiles are very close to the theoretical prediction ($\lambda\text{eff} \cdot F = 4.2\ \mu\text{m}$). The diffraction efficiency at $\lambda = 632.8$ nm was measured to be 56%. The linear dimension of the spot size in the depth direction is confined by the waveguide depth which is 10 μm for the reported device shown in Fig. 2. The wide transmission bandwidth and the GRIN characteristic of the polymer thin film allows the formation of a visible waveguide lens on a lossy high index substrate such as GaAs. The GRIN characteristic makes the formation of guided wave device transferable to any substrate of interest and the wide transmission bandwidth significantly expands the communication bandwidth of the signal carrier beams. Availability of the waveguide hologram and the GaAs-based transceiver circuitry will greatly enhance the chip-to-chip and module-to-module optoelectronic interconnects using the polymer/III-V material system combination. Implementation of the

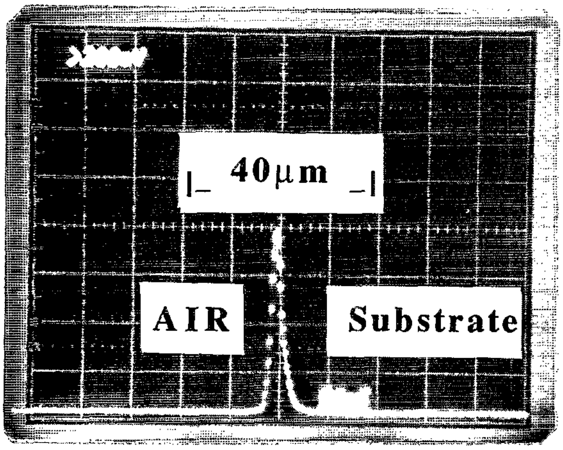
TABLE I. Designed parameters and measured performance of an off-axis chirped grating lens.

Film index	1.4–1.6 (graded index)
Substrate index	3.4
Waveguide thickness	10 μm
Graded index profile	semi-exponential[a]
Waveguide effective index	1.47
Chirp rate	680/mm
Focal length	35 mm
F No. ΔN_{eff}	10–0.2
Diffraction limited spot size (μm) (1/e)	4.2 μm
Measured 3 dB width (1/e)	5.6 μm
Angular field of view (deg)	6°
Waveguide propagation loss	0.1–1.0 dB/cm

[a]Reference 17.



(a)



(b)

FIG. 4. Measured focal spot intensity distribution profiles in the (a), horizontal and (b). Depth directions using a linear charge coupled photodetector array.

GRIN polymer waveguide lens array will also facilitate the waveguide to fiber coupling when the fanout beam size of the waveguide-based wavelength division demultiplex[18] is larger than the diameter of the output fiber.[9]

The locally sensitized photolime gel exhibits an index modulation as high as 0.2.[6] Using the phase grating characteristics, we can multiplex a large number of chirped grating lenses in the same emulsion area.[9] An important implication of the multiplexibility is the feasibility of constructing two-dimensional signal processing with a large number of fanout channels within the same waveguide device. Conventional integrated optical devices sacrifice the third dimension which is important for highly parallel optical signal processing and computing. For example, the integrated optical circuits (IOCs) for synthetic aperture radar (SAR)[16] signal processing require both spatial integration (for range compression) and time integration (for azimuth compression). Range compression is realized through on-chip diagnosis while azimuth compression has to be handled outside of the circuit. The holographic material employed here has a reported index modulation as high as 0.2. Therefore, it is feasible to provide a 1000 $\times$1000 pixel 2D image by using the proposed technique according to the result reported in Ref. 17. The time integration associated with azimuth compression can thus be realized in the same optical guided wave circuit when appropriate detector arrays are integrated.

In summary, we report for the first time the formation of a polymer-based off-axis chirped grating lens working at 632.8 nm on a GaAs substrate. Both single and multiplexed waveguide lenses were formed. The GRIN characteristic of the polymer film allows the formation of such a waveguide circuit on any substrate of interest. The large transmission bandwidth of the polymer film (280–2800 nm) significantly enlarges the optical signal bandwidth for GaAs-based optoelectronic integrated circuits (OEICs). In this letter a chirped grating lens with chirp rate of 680/mm, focal length of 35 mm, and F No. of 10 was successfully demonstrated. A diffraction-limited spot was also demonstrated. Unlike surface-relief gratings, where grating multiplexibility is not achievable because of their binary nature, the holographic waveguide emulsion we employed is a phase grating material with index modulation as high as 0.2. A large number of grating lenses can be multiplexed onto the same area. Finally, two-dimensional pixels—for example, CCD arrays—can be fully integrated onto the same integrated optical circuit. Therefore, an extra degree of freedom for optical signal processing and computing can be provided using IOCs.

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