Aspheric waveguide lenses for photonic integrated circuits

J.-M. Verdiell, M. A. Newkirk, T. L. Koch, R. P. Gnall, U. Koren, B. I. Miller, and L. L. Buhl
AT&T Bell Laboratories, Crawfords Corner Road, P.O. Box 3030, Holmdel, New Jersey 07733-3030

(Received 3 August 1992; accepted for publication 1 December 1992)

We report the fabrication of aspheric waveguide lenses on the InP/InGaAsP material system. A wide aperture ($f/5$) lens working at 1.5 times the diffraction limit is reported. Insertion loss below 1 dB is also measured. The lens is fabricated by a selective chemical etch of a planar waveguide and has potential applications in InP-based photonic integrated circuits.

Indium phosphide is one of the most promising materials for photonic integrated circuits that combine passive optical components such as waveguides, couplers, and filters with active components such as lasers, detectors, and modulators all on the same chip. A waveguide lens is a very useful component for integrated optics and substantial work has indeed been devoted to its achievement. Many lens designs have been demonstrated in thin film and $LiNbO_3$ waveguides, including etched,[1] geodesic,[2,3] Luneburg,[4] Fresnel,[5,6] grating,[7–9] and aspheric[10] lenses. Some work has also been reported in semiconductor materials, mainly with gratings,[11] or composite Fresnel-grating lenses.[12] Due to the high index of the semiconductor material, these approaches usually require writing very fine structures with direct *e*-beam lithography followed by dry etching technology to pattern the wafer. Moreover, the performance of the lens is limited by the diffraction efficiency of the grating and by the background light left by the undiffracted beam. In this letter, we report fabrication of an aspheric lens by wet etching using a standard photolithographic masking step. Wide aperture, very low insertion losses, and spot size close to the diffraction limit are demonstrated.

An effective index change in a planar waveguide can be easily obtained by changing the thickness of the waveguide layer. For creating a precisely controlled index step in a planar waveguide, we can take advantage of wet etching and etch-stop fabrication techniques as shown in Fig. 1. In our sample, a 2000 Å waveguide core layer of $\lambda=1.3$ μm quaternary material is grown on top of the InP substrate, followed by a 200 Å InP etch-stop layer, and another 2000 Å layer of $\lambda=1.3$ μm quaternary material that acts as additional core material. By selectively etching away the upper layer we can create an effective index step with an arbitrary boundary shape in the plane as shown in Fig. 1. Since the effective index in the lens region is lower than the one of the loaded waveguide, the lens curvature appears to be the reverse of an usual lens. One crucial parameter is the size of the index step Δn that can be achieved using this method. As a guideline, for a single spherical surface, the radius of curvature R is given as a function of the focal length f by

$$R=\frac{f\Delta n}{n}. \quad (1)$$

Although the situation is improved by the use of an aspherical surface as we will see, this relation emphasizes that too small a Δn could lead to impractically small radius of curvature. While a large upper core layer will maximize Δn, the mode mismatch at the waveguide transition will eventually lead to high losses. It is also desirable to deal with core thickness compatible with the fabrication of active devices like lasers on the same chip. In order to numerically evaluate Δn, we have computed the mode and effective index of the waveguide with and without the upper core layer, using the transfer matrix method. The transmission loss at the interface was estimated as $\eta=|\int\epsilon_1^*(x)\epsilon_2(x)dx|^2$ for the normalized fields $\epsilon_i(x)$. At the design wavelength of 1.56 μm, the index step is $\Delta n=0.07$ with an η value of 91.5%, corresponding to a loss of 0.39 dB per lens surface. An index step as high as $\Delta n=0.1$ can be achieved by using $\lambda=1.4$ μm material for the upper core and increasing its thickness to 2300 Å. The calculated loss per interface is then 0.63 dB.

Even with these relatively large index steps, applying Eq. (1) with $f=1000$ μm, $\Delta n=0.1$, and $n=3.20$ yields a radius $R=22$ μm. The diffraction limit of such a small

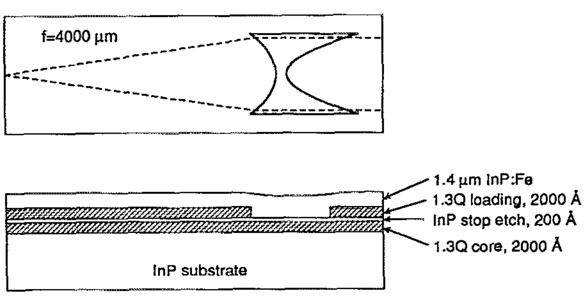

FIG. 1. Principle of the lens fabrication. Top: top view. Bottom: layer structure.

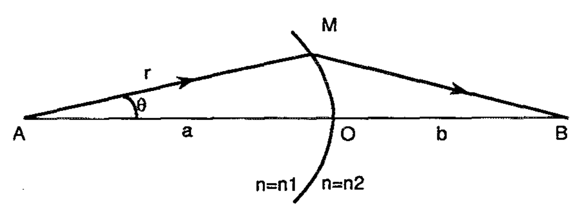

FIG. 2. Notation used in Eq. (3).

 0003-6951/93/080808-03$06.00

lens, even if it were perfectly corrected, would be $d=1.27\, f\lambda/2Rn \approx 13\ \mu m$, which is very wide compared to a standard waveguide width in semiconductor materials. Moreover, the lens performance would be severely affected by spherical aberrations. The use of an aspheric lens relieves both of these problems. The locus M of the points forming an aspheric surface for focusing a pointlike object A to an image point B is given by the Fermat's principle:

$$n_1|AM|+n_2|MB|=\text{const}, \tag{2}$$

where n_1 is the index of the medium at point A and n_2 the index at point B. In polar coordinates notation originating from A (see the notation on Fig. 2), the surface equation is

$$\cos\theta+1=\frac{[a(n_1+n_2)+2n_2b+(n_2-n_1)r][a(n_2-n_1)+(n_2+n_1)r]}{2n_2^2(a+b)r}, \tag{3}$$

where we call O the on-axis point of the lens ($\theta=0$), $a=AO$ and $b=OB$. Figure 3 compares the aspheric surface obtained with $a=800\ \mu m$ and $b=+\infty$ to the equivalent spherical lens with $f=800\ \mu m$. The increase in lens diameter by a factor of more than 2 is readily apparent, together with the obvious departure of the spherical surface from the ideal stigmatic shape. A further twofold gain in aperture is obtained by using two focusing surfaces. Such lenses can be calculated by applying Eq. (3) in two steps, first constructing a surface focusing the object point to a virtual intermediate image, then calculating the surface imaging the intermediate point to the final image point. The extra degree of freedom in choosing the intermediate image can be used to minimize the curvature of the lens surfaces, thereby optimizing the overall size of the lens.

We have fabricated an aspheric lens designed for focusing a collimated input beam to a point at the focal distance of 4000 μm. The use of aspheric surfaces allows a lens diameter of 800 μm (to be compared with the 350 μm diam of an equivalent spherical lens) thus giving an aperture number of $f/5$. The lens was selectively etched in the upper core with a H_2SO_4:H_2O:H_2O_2 solution with the respective 3:1:1 proportions, using SiO_2 as a mask. The sample was then subsequently regrown with 1.4 μm of Fe-doped semi-insulating InP to bury the waveguide according to our standard photonic integrated circuit process.[13]

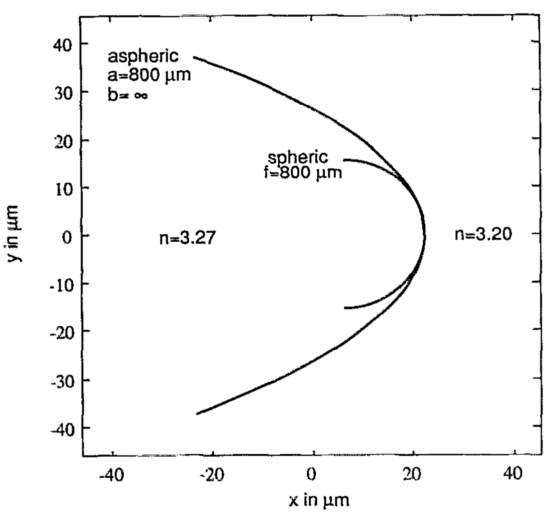

FIG. 3. Comparison of a spheric and an aspheric focusing surface.

We tested the lens using a collimated beam coupled to the waveguide by a cylindrical lens. The focused spot was then imaged on an infrared camera using a microscope objective. The sample length on the focusing side was 3880 μm, which was slightly short of the expected focal distance. The focusing point occurred in the air, 100 μm away from the cleaved facet. Correcting for the refraction at the semiconductor/air interface gives a focal length in the semiconductor of 4200 μm, which is only 5% off the design goal. We attribute this discrepancy to a 5% error in the thickness of the rib loading layer during the growth. A scan through the image of the spot is given in Fig. 4. The width at half-maximum is 3.3 μm and at the $1/e^2$ point is about 4.6 μm. This is approximately 1.5 times the calculated diffraction limit in the air, not taking into account the aberrations occurring at the facet. Note that it is difficult to know with precision if the lens is really working at the diffraction limit, since the exact beam profile illuminating the lens is not known. In our calculations, we used the $1/e$ criterion for the beam diameter both at the lens and at the focal point.[14] We evaluated the insertion loss of the lens by comparing the throughput of a straight portion of the planar waveguide to a portion of the same length including a lens. The insertion loss is found to be less than 1 dB, in good accordance with the theoretical calculation of 0.78 dB.

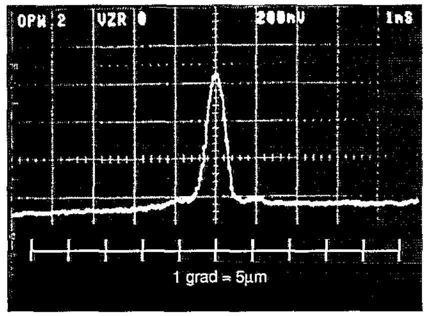

FIG. 4. Scan at the focal plane demonstrating 3.3 μm spot size at half-maximum (horizontal scale=5.58 μm per division).

In summary, we have analyzed the design of aspheric waveguide lenses in semiconductor materials. We have fabricated a lens with 1.5 times diffraction limit performance, less than 1 dB insertion loss and $f/5$ aperture. The size of the focused spot makes it very attractive for applications requiring coupling to waveguides, and the processing technique is simple and compatible with the fabrication of photonic integrated circuits on InP-based material.

[1] R. Ulrich and R. J. Martin, Appl. Opt. **10**, 2077 (1971).
[2] E. Spiller and J. S. Harper, Appl. Opt. **13**, 2105 (1974).
[3] B. Chen and O. G. Ramer, IEEE J. Quantum Electron. **QE-15**, 853 (1979).
[4] F. Zernicke, Opt. Commun. **12**, 379 (1974).
[5] P. R. Ashley and W. S. C. Chang, Appl. Phys. Lett. **33**, 490 (1978).
[6] T. Suhara, K. Kobayashi, H. Nishimara, and J. Koyama, Appl. Opt. **21**, 1966 (1982).
[7] S. K. Yao and D. E. Thompson, Appl. Phys. Lett. **33**, 635 (1978).
[8] C. Warren, S. Forouhar, and W. S. C. Chang, Appl. Phys. Lett. **43**, 424 (1983).
[9] J.-M. P. Delavaux and W. S. C. Chang, IEEE J. Quantum Electron. **QE-21**, 86 (1985).
[10] D. Y. Zang and C. S. Tsai, Appl. Phys. Lett. **46**, 703 (1985).
[11] S. Ura, M. Morisawa, T. Suhura, and H. Nishihara, Appl. Opt. **25**, 1369 (1990).
[12] T. Q. Vu, J. A. Norris, and C. S. Tsai, Appl. Phys. Lett. **54**, 1098 (1989).
[13] T. L. Koch and U. Koren, IEEE J. Lightwave Tech. **8**, 274 (1990).
[14] A. E. Siegman, *Lasers* (University Science Books, Mill Valley, CA, 1986), Chaps. 17.1 and 17.2.