Chirped-grating output couplers in dielectric waveguides*

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(Received 4 August 1976; in final form 29 November 1976)

This paper reports on the method of fabrication and first experiments of chirped (variable period) gratings in a dielectric waveguide. Such gratings, which are proposed as a new optical building block, are used in this work as focusing output couplers.

PACS numbers: 84.40.Wv, 42.80.Lt, 42.82.+n, 42.80.Fn

Periodic perturbations such as surface corrugations are often used for input or output couplers in dielectric waveguides.[1] A guided optical mode can be coupled out by surface gratings at an angle ϕ with respect to the film surface, where ϕ is determined by the propagation constant β of light in the waveguide and by the period Λ. If the output coupler consists of a grating with a variable period $\Lambda(z)$, then, for a given propagating mode, different parts of the coupler would launch the light out in different directions. It is conceivable that all these directions will intersect at a common point in such a way that the light will be focused outside the waveguide.

To ensure this type of focusing we fabricated the grating holographically by exposing a photoresist layer on top of the waveguide to the interference of a collimated laser beam and a cylindrically focused beam. The photoresist grating which remained after development served as a mask through which the grating was replicated, by ion etching, onto the waveguide surface. Similar exposure schemes have been used for the fabrication of holographic lenses.[2]

The setup used for the fabrication of chirped gratings is shown schematically in Fig. 1. A thin layer of recording material is exposed to the interference pattern of a collimated laser beam with a converging beam. The converging beam is generated by a cylindrical lens of focal length f and width d. The bisector of this beam subtends an angle θ with the collimated beam. The coordinates x_f and z_f of the focal point P are simple geometrical functions of f, d, θ, and L, where L is the length of the recorded pattern (see Fig. 1). One can assume that the transmission function t of the recording medium is proportional to EE^* [3] and derive the following expression for t:

$$t=\beta(1+\cos\{kz\sin(\tfrac{1}{2}\theta)+k[(z-z_f)^2+x_f^2]^{1/2}\}), \tag{1}$$

where β is a proportionality factor. The period $\Lambda(z)$ can now be written

$$\Lambda(z)=\frac{\lambda}{\sin(\frac{1}{2}\theta)+(z-z_f)[(z-z_f)^2+x_f^2]^{-1/2}}. \tag{2}$$

The period is therefore a function of λ, θ, f, d, and L. Each of these can be changed, independently, so as to give a different variation $\Lambda(z)$.

The interference pattern described above was used, as discussed above, to fabricate chirped gratings on top of sputtered glass waveguides.

Consider next the dielectric waveguide shown schematically in Fig. 2. The surface of the waveguide is corrugated over a length L, and the corrugation period is given by Eq. (2). For a given propagating mode with a propagation constant $\beta=kn_1\cos\theta_1$, the light coupled out at a point z' along the grating will propagate in air according to

$$\exp(i\{k_z(z')z+[(\omega/c)^2-k_z^2(z')x]^{1/2}\}),$$

where $k_z(z')=\beta-2\pi/\Lambda(z')$. If we define $\beta_0\equiv k_z(0)=\beta-2\pi/\Lambda(0)$ and $\beta_L\equiv k_z(L)=\beta-2\pi/\Lambda(L)$, it can now be shown that the light will be focused by the chirped grating at a point $P(x_\lambda, z_\lambda)$ whose coordinates are given by

$$z_\lambda=\frac{\beta_0 L(k^2-\beta_L^2)^{1/2}}{\beta_0(k^2-\beta_L^2)^{1/2}-\beta_L(k^2-\beta_0^2)^{1/2}}, \tag{3}$$

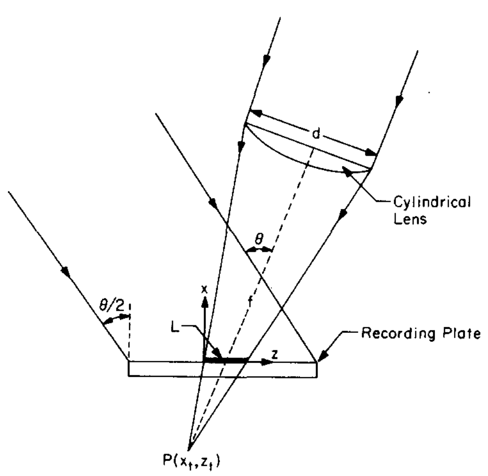

FIG. 1. Recording arrangement and geometry for the fabrication of chirped gratings.

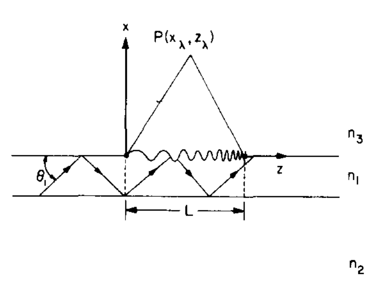

FIG. 2. Geometry for a chirped grating etched on the top surface of a waveguide of index n_1. The substrate has an index n_2, and n_3 is the index of refraction of air. A waveguide mode will focus at point $P(x_\lambda, z_\lambda)$ depending on the waveguide, the chirp of the grating, and the wavelength.

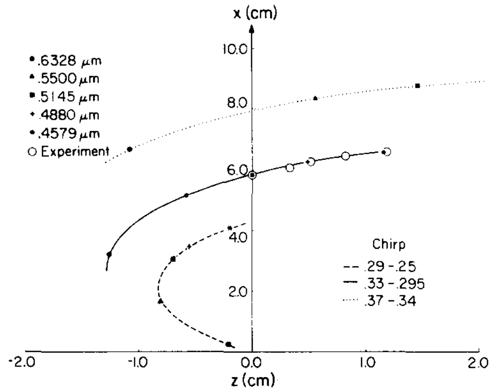

FIG. 3. Experimental and theoretical results of the focusing of light for the corrugated structure used. The solid line represents the theoretical position of the focus as a function of wavelength. The solid dots represent the focus of the prominent lines of the Ar^+ and HeNe lasers. The large circles are the experimental points for these wavelengths as measured with a two-dimensional translation probe.

$$x_\lambda = [(k^2 - \beta_0^2)^{1/2}/\beta_0]\, z_\lambda. \qquad (4)$$

The focal-point coordinates thus depend on the chirp of the gratings, on the waveguide, and on the wavelength of the guided mode. Some examples of the variation of the focal point with wavelength and with chirping are given (for a particular waveguide) in Fig. 3.

To illustrate the focusing effect we designed a waveguide to focus light a few centimeters away from the waveguide. We first used ion sputtering to deposit a layer of 7059 glass on a regular microscope slide. The refractive index of the waveguide was determined by the prism coupler method[4] and was found to be 1.565. The thickness of the deposited layer was determined by Sloan Dektak. The thickness was 1.35 μm and was found to be uniform within 5% over the region of interest. A thin layer of undiluted AZ-1350B Shipley photoresist was then spin coated on the waveguiding layer at 3600 rpm. The photoresist was prebaked at 125 °C for 25 min and then exposed to the interference pattern between the collimated beam and the converging beam. In this experiment we used the $\lambda = 4579$ Å line of an Ar^+ laser, with 1.0 mW/cm^2 per leg. The other variables were $\theta = 94.5°$, $F = 1.33$, and $L = 1.1$ cm. The photoresist layer was exposed for 60 sec, and then developed for 10 sec in AZ-303A developer. Chirped gratings were thus obtained and the grating period was measured and found to vary between $\Lambda(0) = 0.295$ μm and $\Lambda(z = 1.1\text{ cm}) = 0.33$ μm. The photoresist was then baked in vacuum, and the chirped gratings were transferred onto the waveguide using the same ion beam etching machine.

We calculated the position of the focal point $P(x_\lambda, z_\lambda)$ for various lines of the Ar^+ laser. For each line, and for the waveguide used, we calculated the propagation constant and obtained x_λ and z_λ. The results of these calculations are shown in Fig. 3, both for the chirped gratings used and for other chirped gratings.

In the experiment we used a prism coupler to couple light from an Ar^+ laser into the waveguide. The light coupled by the grating was found to focus to a line normal to the xz plane. The x-z coordinates of this line were measured for various lines of an Ar^+ laser. The experimental points are also shown in Fig. 3, and are found to fit well to the theoretical curve. It should be noted that the focal point moves 1.2 cm when the wavelength is changed from 4579 to 5145 Å.

In conclusion we demonstrated in this work the fabrication of a chirped-grating output coupler in an optical waveguide. This structure focuses light outside the waveguide while simultaneously separating between propagating beams of different wavelengths.

Various integrated optics components are based on a periodic perturbation. Such components as narrowband reflection filters,[5] beam splitters,[6] distributed feedback lasers,[7] distributed Bragg reflectors,[8] and grating couplers[1] are all based on a periodic perturbation. Very often the perturbation takes place as a surface corrugation. The addition of a new variable, chirping, into these components is bound to open up new possibilities in their utilization.

The authors wish to thank Professor N. George for many helpful discussions and D.R. Armstrong for his assistance.

*Research supported by Air Force Office of Scientific Research.

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