Graded refractive index waveguides with metal cladding

LIN Sheng-qiang, LI Yu-shan, and JIN Feng
Changchun Institute of Physics, Academia Sinica

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A silver-metal layers has been deposited on the glass waveguide formed by ion exchange and thereby a graded index waveguide with metal cladding has been made. Its eigenvalues have been found by a ray optics method. Experimental results show that the measured values of effective indices agree with the theoretical ones.

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I. INTRODUCTION

In optical integrated circuits, a deposited metal layer on the dielectric waveguide is often requisite for fabricating many optical waveguide devices, e.g. electrodes of thin film laser, optical waveguide detectors, electrooptic and magnetooptic modulators, and some passive devices as polarizers, mode-filters, etc.

As compared with usual dielectric waveguides, those with metal cladding had obvious difference in propagation properties. Further research is helpful not only for clarifying the mechanism of a large group of optical waveguide devices, but also for exploring new waveguide devices. In optical integrated circuits, the graded index waveguides such as the Ti diffusion $LiNbO_3$ waveguide, glass waveguide formed by ion exchange are often used. It is significant to study the propagation properties of graded index waveguides with metal cladding.

Most previous research work was done on metal-clad slab waveguides with stepped index profile. For this, the simple analytic eigenvalue equation can be derived from Maxwell's equation system, although the treatment of its boundary value problem is more complex than that of the slab waveguides without metal cladding. Opposite to this, strict treatment of the boundary value problem from Maxwell's equation system is more complex for the graded index waveguides with metal cladding.

In our laboratory, a silver layer was deposited on the ion exchange glass waveguide to form the graded index waveguide with metal cladding. Its eigenvalues were found by a ray optics method, and compared with measured results.

II. EIGENVALUE EQUATION

The graded index waveguide with metal cladding and its coordinates are shown in Fig. 1, where x and z axis are along the direction of thickness and propagation, respectively; M and $n(x)$ are refractive indices of metal layer and wave-guiding layer, respectively. The complex index of metal layer may be expressed as

$$M^2 = K = K_r + jK_j \qquad (1)$$

where K is the relative dielectric constant, K_r and K_j are its real and imaginary part, respectively. The refractive index of wave-guiding layer may be expressed as

$$n^2(x) = n_b^2 + (n_s^2 - n_b^2) f(x) \qquad (2)$$

where n_s and n_b are the indices of the surface ($x = 0$) and substrate ($x \to \infty$) of the dielectric waveguide, respectively; $f(x)$ is the index profile function, which is equal to 1 at $x = 0$, and decreased to zero monotonically as x increases. Because the metal index is complex, the eigenvalue of dielectric waveguide with metal cladding is also complex. The complex eigenvalues are not calculated in this paper, but the real parts are found in particular cases.

When the real part of the metal dielectric constant is much larger than its imaginary, that is,

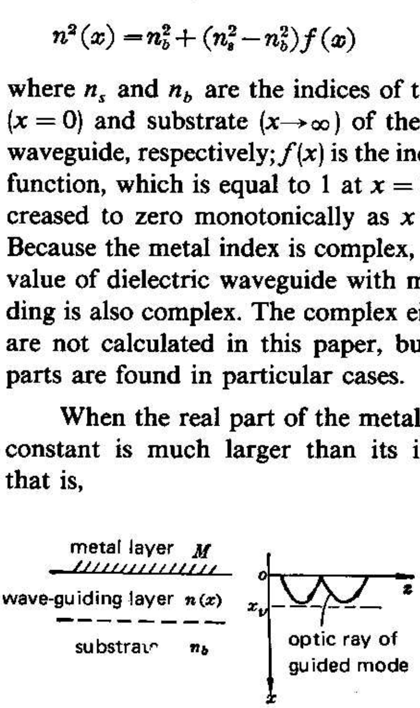

FIG. 1. Graded index waveguide with metal cladding and its coordinate

$$|K_r/K_j| \gg 1 , \tag{3}$$

its imaginary part may be omitted; then the eigenvalue equation of graded index waveguide with metal cladding is easily derived, and expressed as[1]

$$k\int_0^{x_\nu} [n^2(x)-M_\nu^2]^{1/2}dx = \nu\pi + \frac{\pi}{4} + \phi_{mg} \tag{4}$$

where $k = 2\pi/\lambda$ and λ are the propagation constant and wavelength of optical wave in vacuum, respectively; ν is the mode order number of guided mode, and taken as the positive integer beginning from zero; M_ν is the real part of effective index of νth order mode; $M_\nu k$ is the propagation constant of νth order mode along z direction; x_ν is coordinate of optical tunnel point (i.e., optic ray turning point) of νth order mode; $2\phi_{mg}$ is the phase-shift total reflected on the interface of metal and waveguide, which is given by

$$\phi_{mg} = \tan^{-1}\left(\frac{n_s^2}{K_r}\right)^\rho\left(\frac{M_\nu^2-K_r}{n_s^2-M_\nu^2}\right)^{\frac{1}{2}} \tag{5}$$

where $\rho = 0$ and 1 are corresponding to TE and TM modes, respectively.

In our experiment, a glass waveguide formed by ion exchange with metal (Ag) cladding was used, for which the index profile function of wave-guiding layer is a second-order polynomial[2]

$$f(x) = 1-\left(\frac{x}{d}\right)-b\left(\frac{x}{d}\right)^2 \tag{6}$$

therefore, the index profile is

$$n^2(x) = n_s^2-(n_s^2-n_b^2)\left[\left(\frac{x}{d}\right)+b\left(\frac{x}{d}\right)^2\right] \tag{7}$$

where d is the effective diffusion depth, and b is the coefficient of the second-order term. The dielectric constant of silver-metal at 6328 Å laser wavelength is

$$\begin{cases} K = -16.32 - j0.5414 \\ K_r = -16.32, \ K_j = -0.5414 \end{cases} \tag{8}$$

in which its real part is much larger than imaginary part. Substituting Eq. (7) into Eq. (4), and using the property of the optical tunnel point [i.e., $n(x_\nu) = M_\nu$,] the eigenvalue equation of the glass waveguide formed by ion exchange with metal (Ag) cladding is derived, that is,

$$\frac{kd}{4b}\left[\frac{H}{\sqrt{4b(n_s^2-n_b^2)}}\left(\frac{\pi}{2}-\sin^{-1}\sqrt{\frac{n_s^2-n_b^2}{H}}\right) - \sqrt{n_s^2-M_\nu^2}\right] = \nu\pi+\frac{\pi}{4} - \tan^{-1}\left|\frac{n_s^2}{K_r}\right|^\rho\left(\frac{M_\nu^2+|K_r|}{n_s^2-M_\nu^2}\right)^{1/2} \tag{9}$$

where

$$H = (n_s^2-n_b^2)+4b(n_s^2-M_\nu^2) \cdot \tag{10}$$

For the given waveguide parameters (i.e., n_s, n_b, d, and b), the effective index of guided mode (M_ν) may be found from Eq. (9). The real part of the eigenvalues can be given only from Eq. (4) and Eq. (9). In order to find the complex eigenvalues, it is necessary to develop an approximate method treating complex eigenvalues.

III. MEASUREMENT OF EIGENVALUES

A glass microscope slide was immersed in silver nitrate solution at 320 °C for 1 minute, forming a graded index waveguide due to exchange between Na^+ and Ag^+ ions. In this waveguide, two TE modes and two TM modes are supported at 6328 Å laser wavelength. Its effective indices (N_ν) were measured using a prism coupler, and listed in Table I.

For the second-order polynomial index profile, Eq. (7), the eigenvalue equation of the glass waveguide formed by ion exchange is[2]

$$\frac{kd}{4b}\left[\frac{Q}{\sqrt{4b(n_s^2-n_b^2)}}\left(\frac{\pi}{2}-\sin^{-1}\sqrt{\frac{n_s^2-n_b^2}{Q}}\right) - \sqrt{n_s^2-N_\nu^2}\right] = \nu\pi+\frac{\pi}{4} + \tan^{-1}(n_s^2)^\rho\left(\frac{N_\nu^2-1}{n_2^s-N_\nu^2}\right)^{1/2} \tag{11}$$

where

$$Q = (n_s^2-n_b^2)+4b(n_s^2-N_\nu^2) \tag{12}$$

TABLE I. The measured values of effective indices (N_ν) for the glass waveguide formed by ion exchange (at $\lambda = 6328$ Å)

effective index	TE mode	TM mode
N_0	1.5538	1.5525
N_1	1.5141	1.5130

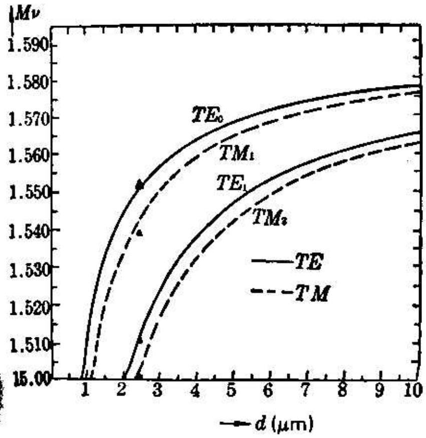

FIG. 2. Theoretical $M_v \sim d$ curves of glass waveguide formed by ion exchange with metal (Ag) cladding *("▲" points respresent measured values)* (μm)

the meaning of ρ is the same as above. Substituting the measured values of the effective index (N_v in Table I) into Eq. (11), four simultaneous eigenvalue equations were obtained. Using computer, four parameters of waveguide were found by the nonlinear method such as $n_s = 1.5950$, $n_b = 1.500$, $d = 2.4$ μm, and $b = 0.62$. On the glass waveguide formed by ion exchange, a silver-metal layer with about 1000 Å thickness was deposited using a vacuum evaporation technique. Since its thickness is larger than the permeated depth of optical wave among metal layer, the silver film may be considered as an infinite, thick metal layer, theoretically. Substituting the above waveguide parameters into Eq. (9), the quantitative relation of the effective index (M_v) to the diffusion depth (d) for glass waveguide formed by ion exchange with metal (Ag) cladding was solved using a computer, and theoretical $M_v \sim d$ curves of TE_0, TE_1, TM_1 and TM_2 modes were plotted (see Fig. 2).

In the dielectric waveguide with about 1000 Å thick metal cladding, every TE modes and TM modes except fundamental TM mode *can be excited using the prism coupler. These* modes have a little propagation loss, and its propagation streak in the waveguide can be observed by the eye. The effective indices of TE_0, TE_1, TM_1, and TM_2 modes were measured us*ing a prism coupler, and listed in Table II, and* represented by "▲" points on $M_v \sim d$ curves in Fig. 2. For TM_0 mode having large propagation loss, by means of detecting the light intensities reflected on the prism bottom as change of incidence angle, the synchronous incidence angle may be measured using optoelectronic instruments, therefore its effective index can be determined. We fail to measure effective index of TM_0 mode because of restriction by conditions.

TABLE II. The measured values of effective index (M_v) for the glass waveguide formed by ion exchange with metal (Ag) cladding (at $\lambda = 6328$ Å)

effective index	TE mode	TM mode
M_0	1.551	not measured
M_1	1.512	1.540
M_2	cut off	1.509

As shown in Fig. 2, the measured values of the effective index (M_v) agree well with theoretical values. For a TM_1 mode having evident difference, the difference between the measured and theoretical values is only about 0.3%, but within the error range caused by omitting imaginary part of metal dielectric constant. This fact shows that more accurate eigenvalues can also be found by a ray optics method when the imaginary part of dielectric constant is omitted for some metal cladding such as silver.

[1] T. Tamir, "Integrated Optics", Springer-Verlag, Berlin Heidelberg, New York (1975), Chap. 2.

[2] G. Stewart *et al.*; *IEEE J. Quant. Electr.*, 1977, **QE-13**, 192.

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