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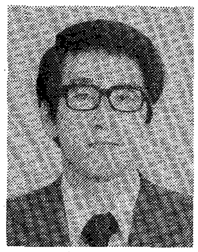

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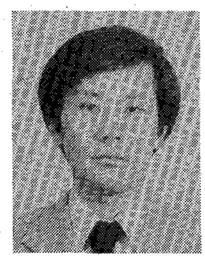

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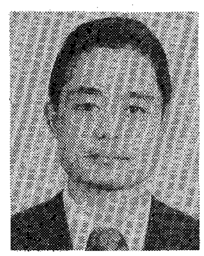

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Measurement and Analysis of Periodic Coupling in Silicon-Clad Planar Waveguides

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***Abstract*—Computer modeling studies indicate that planar dielectric waveguides clad with silicon exhibit a damped periodic oscillation in their attenuation and phase characteristics. The effect is due to a periodic coupling between the lossy, guided modes in the silicon film and the TE_0 mode of the dielectric waveguide. Experimental confirmation of the periodic coupling for a wavelength of 632.8 nm is presented. Propagation characteristics for a wavelength of 1150 nm were investigated for application in integrated optical modulators. Frequency filtering properties of silicon-clad waveguides are also examined and it is shown that the silicon thickness controls the filter response curve.**

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I. Introduction

METAL-clad optical waveguides have been studied extensively and have found considerable application in electrooptic and magnetooptic modulators [1]–[5]. Semiconductor-clad or positive permittivity metal-clad waveguides are characterized by high attenuations which have severely limited their application, although they may be useful as cutoff polarizers or attenuators [6], and more recently, for optical control of millimeter wave propagation [7], [8]. We discuss further applications for these semiconductor-clad waveguides [9] and report, in this paper, the experimental confirmation of the predicted characteristics. Frequency filtering is also suggested as an application for these clad guides in the optical propagation region based on predictions presented here.

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The permittivity of a semiconductor is given by

$$\epsilon_R = \epsilon' - j\epsilon'' = \epsilon' - \frac{j\sigma}{\omega\epsilon_o} \tag{1}$$

where σ is the conductivity of the material at frequency ω. This can also be expressed in terms of the refractive index of the semiconductor as

$$\hat{n} = \epsilon^{1/2} = n - jk \tag{2}$$

where n and k are the real and imaginary parts of the refractive index, respectively. Values for the thin amorphous semiconductor films of interest are highly dependent on the preparation technique used [10].

Lee *et al.* [7] have shown that both the real and imaginary portions of the permittivity vary with incident light; however, the variation in the real part is small compared to the imaginary portion. It is assumed, then, that if light is incident on the semiconductor film, electron-hole pairs are created and only the conductivity varies according to

$$\sigma = \sigma_o e \Delta n(\mu_e + \mu_h)$$

where μ_e and μ_h are the electron and hole mobilities, respectively, and Δn is the number of generated electron-hole pairs. The imaginary portion of the permittivity is thus changed proportional to the number of generated pairs.

As previously reported [9], planar waveguide structures utilizing this externally induced conductivity change have been analyzed and it was shown that the attenuation and mode index of the propagating mode are significantly altered by conductivity changes in the semiconductor cladding. An amplitude modulator and phase modulator were proposed using these results. Furthermore, it was noted that the planar waveguide structures exhibit a periodic coupling between modes in the dielectric waveguide and semiconductor cladding. The experimental confirmation of the periodic coupling from the waveguide modes to the semiconductor cladding is discussed in Section II for propagation at 632.8 nm. Section III examines the waveguide characteristics at a wavelength below the bandgap of the silicon cladding (1150 nm). Based on the previous analysis of the characteristics of the guide at 632.8 nm and the results of Section III, it was observed that the silicon film could be used as a frequency filter. The frequency characteristics are investigated in detail in Section IV and these results suggest the use of such clad waveguides as coarse frequency filters.

II. Theory and Experimental Verification

Computer modeling studies of four-layer, silicon-clad, planar optical waveguides indicate that the attenuation behaves as a damped sinusoid with increasing semiconductor thickness [9]. Experimental confirmation of this predicted effect is presented after a brief review of previous predictions.

The four-layer planar waveguide structure under consideration is shown in Fig. 1 where the guided light is propagating in the z direction in the dielectric (N_3), and it is assumed there is no variation in the y direction. All materials are lossless except for the silicon (N_2). The dispersion relations for this structure are well known and two methods of solution

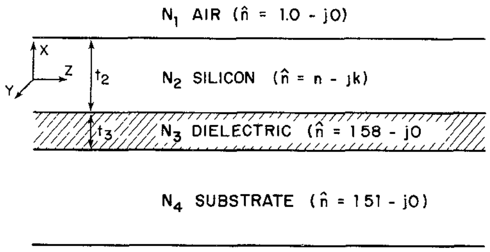

Fig. 1. Four-layer planar waveguide structure.

for the complex mode propagation constant ($\alpha + j\beta$) have been described previously [11], [12].

The waveguide consists of a semi-infinite glass substrate, a dielectric core of thickness 1 μm, a silicon cladding varying from 0.01 to 10 μm in thickness, and a semi-infinite layer of air. A free-space wavelength of 632.8 nm was assumed and all material parameters shown in Fig. 1 are for this wavelength. It should be noted that permittivity values for thin amorphous semiconductor films depend on the method of deposition and any impurities deliberately or accidentially added to the semiconductor [13], [14]. Thus, values assumed in these calculations may vary from those of the experimental films since no attempts were made to measure the permittivity of the experimental films at optical frequencies.

Silicon was investigated as a semiconductor cladding and the attenuation curve of Fig. 2 was generated by varying the cladding thickness from 0.01 to 10 μm. All other parameters were held constant in the calculations and results were confirmed using the two computer solution techniques [11], [12]. It was initially expected that decreasing the lossy cladding thickness to 0.01 μm would reduce the attenuation to zero in a well-behaved manner; however, the results were not as expected below a silicon thickness of 1.0 μm.

Experimental confirmation of the oscillatory behavior of the attenuation versus silicon thickness curve was subsequently attempted. Low-loss, single-mode optical waveguides were diffused into soda-lime glass from a sodium nitrate/silver nitrate melt using an ion-exchange fabrication technique [15]-[18]. Uniform silicon films 1 mm wide and extending across the waveguide were deposited using a radio-frequency sputtering system [19]-[21]. For each run, the system was prepumped to a base pressure less than 5×10^{-6} torr and all sputtering was performed in an argon atmosphere at a pressure of 10^{-2} torr. A number of uniform silicon films with thicknesses in the range of 0.02-0.4 μm were fabricated. High predicted attenuations in the silicon-clad guide along with severe experimental inaccuracies in either the fluid coupler or the sliding-prism attenuation measurement technique [3] has made quantitative confirmation difficult. Thus, a photographic technique was employed for confirmation of the behavior shown in Fig. 2.

As Fig. 3 indicates, qualitative confirmation of the damped oscillatory behavior of the attenuation versus silicon thickness curve has been successful. A 5 mW He-Ne (632.8 nm) laser was coupled into the silicon-clad guide using a prism coupler. Fig. 3 is a top view of the coupler and silicon-clad planar waveguide with propagation from left to right. In each of the three photographs, the coupling into the waveguide was

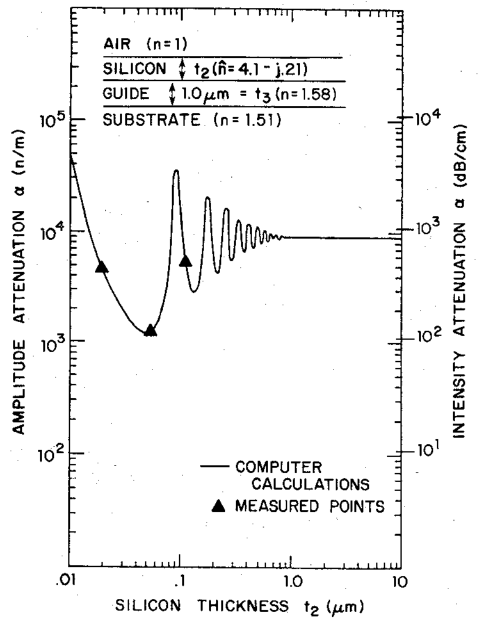

Fig. 2. Attenuation characteristics of silicon-clad waveguide (TE_0 mode, wavelength = 632.8 nm).

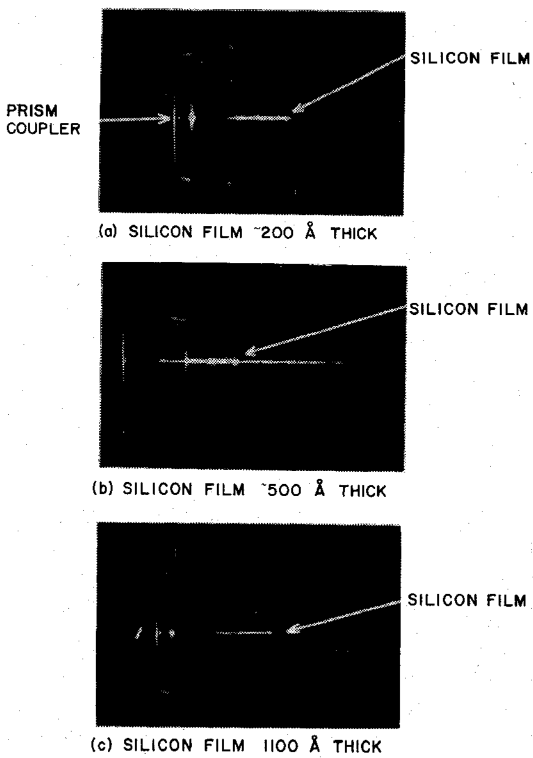

Fig. 3. Experimental measurements of waveguide attenuation.

maximized. All photographic exposures are 5 s, f2, ASA 400 film. Uninterrupted propagation occurs until the beam encounters the 1 mm wide silicon film at which point it may suffer a large attenuation. Slight differences in the beam intensity to the left of the slilcon film are due to differences in coupling efficiency and scattering in the individual waveguides. For a silicon film 200 Å thick [Fig. 3(a)], the beam is clearly attenuated as computer calculations predict. For a film 500 Å thick (a predicted minimum on the attenuation thickness curve of Fig. 2) nearly uninterrupted propagation occurs [Fig. 3(b)], and for a film 1100 Å thick (a predicted region of high attenuation), the beam is again attenuated [Fig. 3(c)]. The three points labeled "measured" in Fig. 2 correspond to the film thicknesses at which the photographic exposures were taken and are not quantitative amplitude measurements. The principal conclusion which can be drawn from the data is that there is at least one minimum in attenuation which occurs in the thickness range 200–1100 Å. The existence of this local minimum between 200 and 1100 Å was similarly verified with a different set of silicon-clad waveguides. It should be noted that accurate thickness measurements are difficult for silicon films less than 200 Å and that the values for the refractive indexes used in the computer calculations may differ from those of the actual silicon-clad waveguides. Furthermore, predicted high attenuations for subsequent peaks and valleys of the attenuation versus silicon thickness curve make confirmation of the oscillatory behavior for thicker silicon films extremely difficult (i.e., the attenuation for subsequent peaks is greater than 1000 dB/cm). Additional measurements will be required to confirm the absolute attenuation levels observed.

III. Calculations and Analysis at 1150 nm

It has been predicted that the attenuation and mode index of the four-layer silicon-clad guide are significantly altered by conductivity changes in the silicon, and amplitude and phase modulators have been proposed using these results [9]. Calculations were presented for a wavelength of 632.8 nm, and modulation would be accomplished as a result of a change in the semiconductor conductivity via an incident light beam with photon energy above the bandgap of the silicon. It is evident, however, that the 632.8 nm guided wave will inadvertently excite the silicon cladding since it is above the bandgap. To circumvent this problem the wavelength was changed to 1150 nm and the amplitude and phase characteristics of the guide were analyzed. This wavelength is such that the absorption coefficient of amorphous silicon is minimal [22], [27] and appreciable excitation of the silicon cladding due to the 1150 nm guided wave is unlikely. Direct optical modulation, however, would still be realized by altering the conductivity of the silicon with a light beam with photon energy above the bandgap of silicon (in the visible region). Computer predictions of the propagation characteristics of the four-layer silicon-clad planar waveguide at 1150 nm are presented in this section.

The attenuation and phase constant curves of Figs. 4 and 5 were generated by varying the silicon cladding thickness from 0.01 to 1.0 μm (the phase constant β has been normalized by $k_o = 2\pi/\lambda_o$ so that all curves show the mode index). Material parameters shown in Figs. 4 and 5 are for a 1150 nm wavelength. The curves are again similar to exponentially damped sinusoids with extreme values of the mode index (β/k_o) coresponding to the median values (maximum slope) in the attenuation (α) curves. Extreme values of the α curve correspond to median values in the β/k_o curves and the oscillations in both curves approach a median value at 10 μm. Similar behavior was observed for a wavelength of 632.8 nm and results were described as a periodic coupling be-

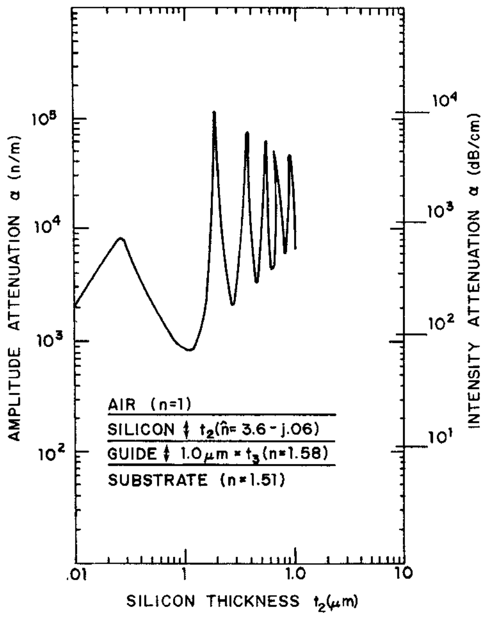

Fig. 4. Attenuation characteristics of silicon-clad waveguide (TE_0 mode, wavelength = 1150 nm).

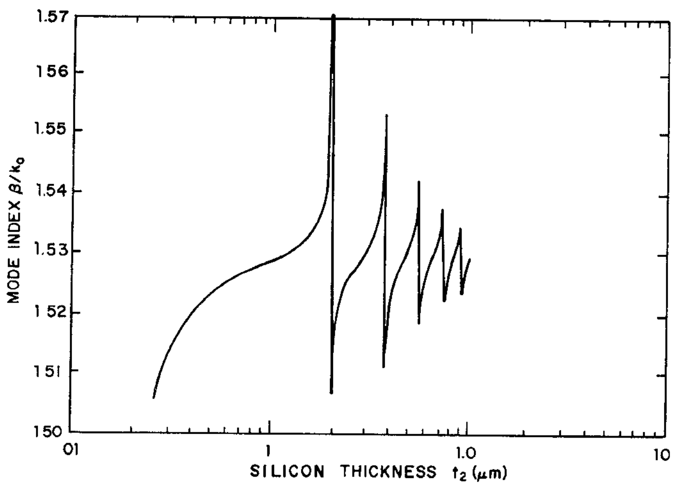

Fig. 5. Mode index characteristics of silicon-clad waveguide (TE_0 mode, wavelength = 1150 nm).

tween the guided mode (TE_0) in the dielectric and the lossy TE′ modes[1] of the semiconductor guide [9]. Figs. 4 and 5 show that such coupling still occurs and the amplitude of the oscillations has increased.

This coupling (or lack thereof) has a profound effect on the attenuation and phase characteristics of the original four-layer waveguide. Therefore, a partial structure consisting of a silicon guiding region surrounded by semi-infinite layers of air and dielectric was analyzed.

The mode index and attenuation constants for the first few low order TE′ modes in the silicon waveguide are shown in Figs. 6 and 7. All modes (except, perhaps the lowest order TE_0' mode) are very lossy and the attenuation increases for the higher order modes. In Figs. 5 and 6, note that a phase

[1] TE_i' denotes guided modes in the semiconductor and TE_i denotes guided modes in the dielectric.

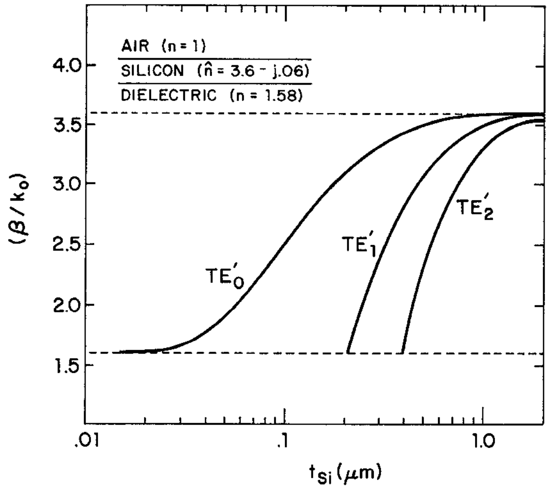

Fig. 6. Mode index characteristics of silicon waveguide (wavelength = 1150 nm).

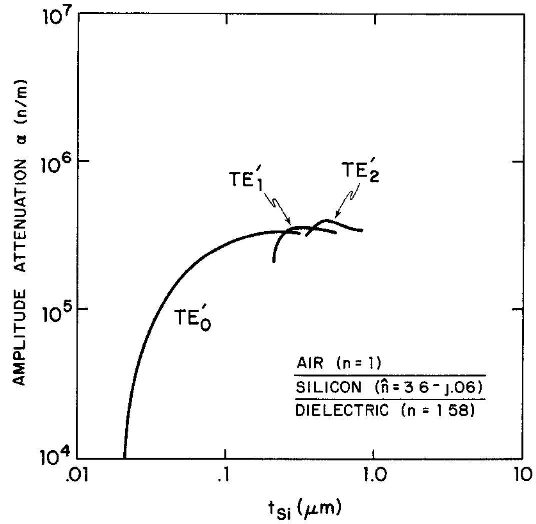

Fig. 7. Attenuation characteristics of silicon waveguide (wavelength = 1150 nm).

match condition occurs between the TE_0 mode in the waveguide and the TE_1' mode in the partial structure (air–silicon–dielectric) at $t_{Si} = 0.2$ μm. This phase match is present at each of the successively higher order TE′ mode cutoff thicknesses and corresponds to the respective attenuation peaks in Fig. 4 for the total structure. The sharp nulls in the attenuation curve, indicating very low coupling efficiency, occur at thicknesses midway between the cutoff value of two adjacent lossy TE′ modes. Note, however, that the first peak on the four-layer attenuation curve (Fig. 4) is considerably lower than the subsequent peaks. This behavior is unlike that of the attenuation curve presented at 632.8 nm (Fig. 2). Observe that the TE_0' mode of the three-layer guide (Fig. 7) is reasonably low-loss, and that, although nearly complete transfer of energy between the guide and the silicon occurs for $t_{Si} = 0.25$ μm, coupling is into a low-loss mode. For the subsequent peaks on the attenuation curve (Fig. 4), coupling is into high-loss modes of the partial structure and the attenuation of the four-layer guide is thus greater. For large silicon thickness, however, the four-layer attenuation curve (Fig. 4) exponentially approaches that of the three-layer structures previously analyzed [23], where the semiconductor layer is considered semi-infinite. Similarly, the abrupt transitions on the mode index curve of the complete structure (Fig. 5) occur when the phase match condition is satisfied and the guided waves couple into successively higher order modes of the partial structure. These results are similar to the power transfer calculations for linearly tapered directional couplers [24]-[26]. Finally, note that the period and amplitude of the attenuation characteristics of the silicon-clad guide are a function of the material permittivities for a given wavelength as Fig. 2 ($\lambda = 632.8$ nm) and Fig. 4 ($\lambda = 1150$ nm) indicate.

Calculations presented in this section demonstrate that the attenuation and mode index of the four-layer silicon clad planar dielectric waveguide behave as exponentially damped sinusoids for a wavelength of 1150 nm. The effect may be explained as a coupling between the basic TE_0 mode of the dielectric waveguide and the high loss TE' modes of the semiconductor guide. The oscillatory behavior of the attenuation and mode index curves, a necessary prerequisite for the direct modulation of the guided beam, is still apparent and detailed calculations of a direct optical modulation scheme at 632.8 nm are presented elsewhere [9]. These calculations at 1150 nm demonstrate that the required modulation technique is still feasible without inadvertent excitation of the silicon cladding by the guided light wave.

IV. Selective Frequency Filtering

The attenuation characteristics of silicon-clad waveguides are a function of the material permittivities for a particular wavelength as Fig. 2 ($\lambda_o = 632.8$ nm) and Fig. 4 ($\lambda_o = 1150$ nm) indicate. Based on the observed change in period and amplitude of the attenuation curve oscillations as the material parameters vary with wavelength, it is evident that selective frequency filtering can be realized with a silicon-clad waveguide. In particular, for a given silicon-cladding thickness, the attenuation will vary drastically as the material permittivities vary with wavelength, and through optimization of the semiconductor cladding thickness, a particular frequency filtering response may be obtained with the clad guide. For example, note that a silicon thickness $t_{Si} = 0.10$ μm lies in a range of high attenuation ($\alpha > 10^4$ n/m) on Fig. 2 ($\lambda = 632.8$ nm), while it is in a region of low attenuation ($\alpha < 10^3$ n/m) on Fig. 4 ($\lambda = 1150$ nm). It is this effect which will be used for frequency filtering. The permittivities of all four materials (air, silicon, guide, substrate) in the planar waveguide structure of interest vary with wavelength; however amorphous silicon is particularly sensitive to frequency variations as Table I indicates [27]. The predicted frequency filtering effect is due almost solely to a change in silicon permittivity. It should be again noted that the permittivity of amorphous silicon is highly dependent upon the method of preparation.

Attenuation versus silicon thickness curves similar to those of Figs. 2 and 4 were generated as the wavelength was allowed to change from 0.35 to 1.55 μm and the permittivities of the four layers consequently varied [10], [27]. All attenuation curves retained their characteristic oscillations; however, the amplitude and period of the oscillations were significantly

TABLE I
Amorphous Silicon Parameters As a Function of Wavelength

Wavelength (microns)	Refractive Index n	k	Relative Permittivity ε'_R	ε''_R
0.35	3.63	2.860	5.0	20.80
0.42	4.53	1.470	18.4	13.40
0.52	4.43	0.900	18.8	8 00
0.57	4.21	0.660	17.3	5.60
0.62	4.11	0.388	16.8	3.20
0.65	4.04	0.289	16.3	2 35
0.69	3.97	0.188	15.8	1.50
0.74	3.88	0.155	15.0	1.20
0.89	3.67	0.068	13.5	0.50
1.00	3.65	0 062	12.3	0.45
1.15	3.59	0.056	12.9	0.40
1.24	3.55	0.039	12.6	0.28
1.55	3.52	0.028	12.4	0.20

altered. Similarly, the mode index versus silicon thickness curves retained their characteristic oscillatory behavior although the frequency and amplitude of the oscillations changed.

Figs. 8-10 were obtained by assuming a given silicon thickness in the four-layer planar structure and allowing the wavelength to vary (and consequently, the material permittivities). The resulting attenuation (dB) for a 1 mm wide silicon bar is plotted vertically in Figs. 8-10.

A high-pass frequency filter is realized in Fig. 8. Insertion loss is less than 7 dB for a wavelength greater than 1.0 μm for the three silicon thicknesses considered ($t_{Si} = 0.09, 0.10, 0.11$ μm), and the extinction for wavelengths less than 0.7 μm is more than 50 dB. The particular filter characteristics in the wavelength region of 0.7-1.0 μm may be adjusted by changing the thickness of the silicon cladding.

Filters with passband wavelengths of 0.7-0.9 μm are shown in Fig. 9. Note that the exact location of the passband may be varied for the three silicon thicknesses of interest (t_{Si} = 0.15, 0.17, 0.19 μm) and that high attenuation (>100 dB) occurs immediately outside of this passband region. Insertion loss, however, is approximately 20 dB.

Even relatively short sections of silicon-clad waveguides are lossy, and for a practical device the insertion loss must be reduced significantly. Thin dielectric buffer layers have been used to lower the attenuation losses of metal-clad dielectric waveguides [28]. These layers are placed between the dielectric core and the metal and act as buffers to remove a large portion of the field from the metal cladding. The effect of a silicon dioxide (SiO_2) buffer layer on the filter response curve was investigated. The results are shown in Fig. 10. A silicon thickness $t_{Si} = 0.13$ μm was assumed and the attenuation versus wavelength was calculated for a four-layer structure. Note that an insertion loss of approximately 40 dB is apparent in the passband region of 632.8 nm, although rapid extinction is evident (>400 dB) immediately outside of the passband region. A silicon dioxide buffer layer ($t_{Si} = 0.2$ μm) of refractive index $n = 1.46$ was then added, and the filter response curve for the five-layer structure was calculated. Insertion loss is now less than 9 dB at a wavelength of 632.8 nm while rapid extinction (>200 dB) is still evident immediately outside of this passband. Further reduction of the passband attenuation may result from optimization of the buffer layer and silicon thicknesses. Although no attempt has been made to optimize the filter characteristics, Figs. 8 and 9 indicate the low fre-

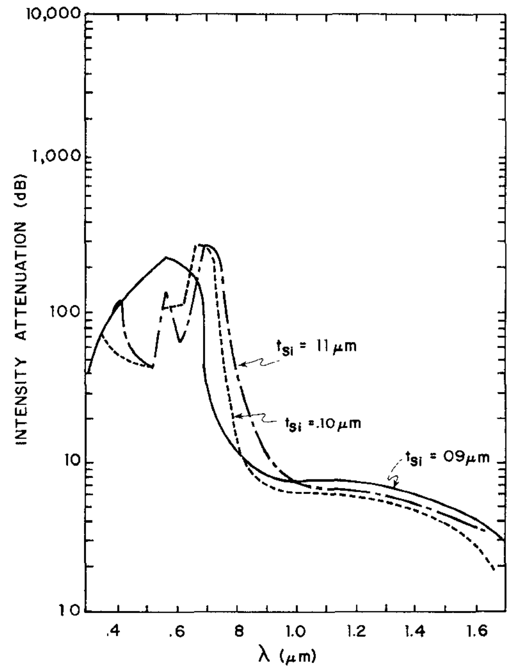

Fig. 8. Frequency response of silicon-clad waveguide (t_{Si} = 0.09, 0.10, 0.11 μm).

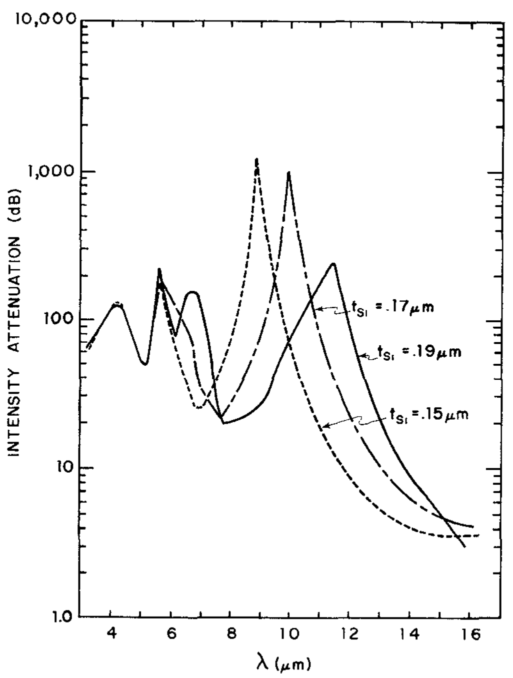

Fig. 9. Frequency response of silicon-clad waveguide (t_{Si} = 0.15, 0.17, 0.19 μm).

quency cutoff and the attenuation peaks may be adjusted by proper choice of cladding thickness.

V. Conclusions

It has been shown that planar dielectric waveguides clad with silicon exhibit a damped periodic oscillation in their attenuation and phase characteristics. The effect is due to a periodic coupling between the lossy guided modes in the silicon film and the TE_0 mode of the dielectric waveguide. Experimental confirmation of this periodic coupling for a

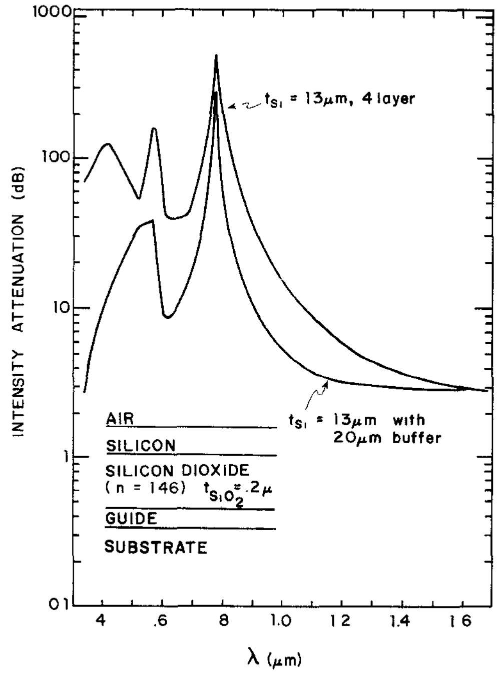

Fig. 10. Reduction in attenuation of filter with SiO_2 buffer layer (n = 1.46, t_{SiO_2} = 0.2 μm).

wavelength of 632.8 nm has been achieved. Calculations for a wavelength of 1150 nm indicate that the attenuation and mode index still retain their oscillatory behavior. Thus, a direct optical modulation scheme through excitation of the silicon cladding is still applicable without inadvertent excitation of the cladding by the guided wave. The silicon-clad guide may also be used as a frequency filter, and the characteristics may be adjusted through optimization of the silicon thickness and through control of a buffer layer. Practical devices are currently being constructed to confirm their predicted characteristics.

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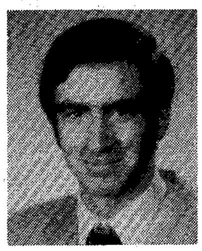
Glen M. McWright (S'81), for a photograph and biography, see p. 634 of the April 1982 issue of this TRANSACTIONS.

T. E. Batchman (S'61–M'66), for a photograph and biography, see p. 634 of the April 1982 issue of this TRANSACTIONS.



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