Guided-Wave Approaches to Spectrally Selective Energy Absorption

A Final Report
prepared for

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

(NASA-CR-182532) GUIDED-WAVE APPROACHES TO SPECTRALLY SELECTIVE ENERGY ABSORPTION Final Report, 25 Jan. 1983 - 2 Mar. 1987 (Arizona Univ.) 14 p CSCL 20N

N88-17892

Unclas

G3/32 0126017

G. I. Stegeman and J. J. Burke
Principal Investigators

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

Grant Number: NAG 3-392

Periods Covered: January 25, 1983 - January 24, 1985
(Optics of Surface Plasmon Polaritons)

January 23, 1985 - March 24, 1986

March 5, 1986 - March 2, 1987

Abstract

Results of experiments designed to demonstrate spectrally selective absorption in dielectric waveguides on semiconductor substrates are reported. These experiments were conducted with three waveguides, formed by sputtering films of PSK2 glass onto silicon-oxide layers grown on silicon substrates. The three waveguide samples were studied at 633 nm and 532 nm. The samples differed only in the thickness of the silicon-oxide layer, specifically 256 nm, 506 nm, and 740 nm. Agreement between theoretical predictions and measurements of propagation constants (mode angles) of the six or seven modes supported by these samples was excellent. However, the loss measurements were inconclusive because of high scattering losses in the structures fabricated (in excess of 10 dB/cm). Theoretic calculations indicated that the power distribution among all the modes supported by these structures will reach its steady-state value after a propagation length of only 1 mm. Accordingly, the measured loss rates were found to be almost independent of which mode was initially excited. The excellent agreement between theory and experiment with respect to the propagation constant leads to the conclusion that experiments with low-loss waveguides would confirm the theoretically predicted loss rates of the different modes, and thus the anticipated spectral selectivity of such structures.

Introduction

This report concludes a four-year study of the possible applications of guided-wave structures to solar energy converters. The study began by examining the application of surface plasmons, particularly the long-range surface plasmons that propagate on thin metal films, and on pairs of such films separated by thin dielectric layers. The results of our theoretical studies of such structures were published early in the program.[1-4] As explained in prior letter reports, our experimental attempts to launch plasmons on thin metal layers by endfire coupling were not conclusive. They were abandoned in 1985 in favor of studying more promising structures, namely dielectric waveguides bounded by semiconducting substrates. The body of this report describes these latter studies.

We begin with a brief description of the theoretical framework, which we have incorporated into a computer program that can compute the real and imaginary parts of the propagation constants of all modes (bound or leaky) that are supported by any collection of homogeneous, isotropic films grown on arbitrary substrates. The real part of the propagation constant yields the mode angle in the guide; the imaginary part defines the loss rate. These were computed for the structures used in the experiments.

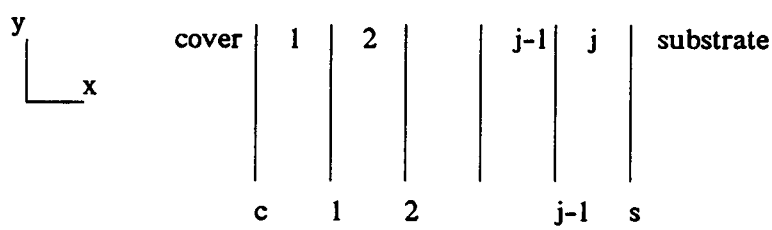
We then describe the experiments, in which grating couplers were used to selectively launch individual modes of our multi-mode guides. The mode angles were measured by noting the angle between the normal to the structure and the direction of the collimated input beam to the grating. The loss rates were measured for initial excitation of each and every mode. Because of scattering, the rates are not characteristic of the modes initially excited, but reflect, rather, the collective loss rates of all the modes due to both absorption and scattering.

The numerical and graphic predictions of theory and the results of experimentation, with respect to both mode angles and losses, are summarized in three tables and two graphs at the end of the report. The agreement with respect to mode angle is excellent. The loss rates are inconclusive, because of scattering. We conclude, because of the excellent agreement for the mode angles, that we are capable of designing spectrally selective waveguide structures for solar energy applications, but incapable of sputtering, with our present facilities, the low-loss waveguides necessary to verify our designs.

Theory

The theory used to calculate the waveguide properties was detailed in a paper by Chilwell and Hodgkinson.[5] We will present a brief summary here.

Consider a stack of dielectric films lying parallel to the yz plane, thus:



This structure will support guided waves if at least one film is surrounded by films of lower refractive index. For true confinement, the cover and substrate indices must both be lower than at least one of the film indices. We write the x and y dependence of the plane-wave fields as $\exp[ik(\alpha x + \beta y) - i\omega t]$, where propagation of the guided modes is in the y direction, there is no variation in z, and the films lie parallel the yz plane. The total field distribution is a superposition of these plane-wave fields. For a plane wave in the cover layer, incident on the stack at an angle θ from the normal to the stack, we have

$$\alpha_j = n_j \cos\theta_j = (n_j^2 - \beta^2)^{1/2} ,$$

$$\beta = n_j \sin\theta_j .$$

If the optical field is known at a single x value, it can be found everywhere with the use of 2×2 matrices. For a single layer we write,

$$\begin{bmatrix} U_{j-1} \\ V_{j-1} \end{bmatrix} = \mathbf{M}_j \begin{bmatrix} U_j \\ V_j \end{bmatrix} ,$$

where $\mathbf{M}_j$ is the field-transfer matrix. For TE modes, U_j and V_j are the complex amplitudes (at the boundary of the j^{th} and $(j + 1)^{th}$ layers) of the electric-field vector and the magnetic-field vector (transverse to the direction of propagation), respectively. These techniques are familiar from thin-film analysis.[6] The field-transfer matrix is given by

$$\mathbf{M}_j = \begin{bmatrix} \cos\Phi_j & (-i/\gamma_j)\sin\Phi_j \\ -i\gamma_j\sin\Phi_j & \cos\Phi_j \end{bmatrix} ,$$

where $\Phi_j = k\alpha_j(x_j - x_{j-1})$ is called the phase thickness of layer j, and $\gamma_j = n_j\cos\theta_j/z_0$, with $z_0 = (\mu_0/\epsilon_0)^{1/2}$. The field-transfer matrix for a stack of layers is equal to the product of the individual layers' matrices,

$$\mathbf{M} = \prod_{j=1}^{J} \mathbf{M}_j .$$

Thus by finding the field-transfer matrix for the entire stack of dielectrics, one can calculate the field distribution throughout the stack for a given α and β.

We can now apply this formalism to determining the guided modes. These modes are evanescent in the cover and substrate, and oscillatory in at least one of the dielectric films. In other words, n_c, $n_s < \beta_r$, where β_r is the real part of β. We require the fields in the cover and substrate to decay exponentially in x; i.e., the evanescent fields. Setting up the relations between the fields in the cover and the substrate and applying the boundary conditions from Maxwell's equations leads to

$$\begin{bmatrix} 1 \\ -\gamma_c \end{bmatrix} U_c = \mathbf{M} \begin{bmatrix} 1 \\ \gamma_s \end{bmatrix} U_s .$$

Solving this equation leads to the modal dispersion equation

$$\chi_M(\beta) \equiv \gamma_c M_{11} + \gamma_c\gamma_s M_{12} + M_{21} + \gamma_s M_{22} = 0 .$$

This equation holds only for discrete values of β, which are the guided modes. By allowing complex dielectric constants, and thus complex β, one can calculate the loss coefficients (due to absorption losses in the films) from β, since the field propagates as $\exp[-k\beta_i y]$, where β_i is the imaginary part of β.

In modeling the experiment described below, a slight change in the formalism is necessary. The substrate layer was silicon, which has a much higher index of refraction than any of the film layers ($n_r \cong 4$). Thus we must relax the requirement of evanescent fields in the substrate ($\beta_r < n_s$).

A program was written to handle an arbitrary number of films with complex indices of refraction. The program finds the roots of the above modal dispersion equation in the complex β plane. From these, the effective mode index β_r and the losses in the guide β_i are calculated for each guided mode.

Experiment

To test the idea of wavelength-dependent coupling, samples were fabricated in which a silicon substrate provided the absorbing dielectric layer. Since the index of silicon is high ($n_r \cong 4$), a low-index buffer layer is needed between the guiding layer and the silicon. To achieve this, the wafers were baked in an oxygen atmosphere. This resulted in a layer of silicon dioxide on top of the silicon. The SiO_2 acted as the buffer layer between the waveguide and the silicon substrate. Buffer layers were fabricated with thicknesses of 0.74, 0.506, and 0.256 μm.

A relatively low-index glass, PSK2, was sputtered onto these processed silicon substrates to form the actual guiding layer. The deposition of this glass was a major stumbling block. The sputtering system in use was poorly designed and was host to a large number of materials. The system spent a large portion of the time under repair or in transition between different sputtering materials. Although many waveguides of the PSK2 glass were fabricated, linear scattering losses on glass substrates were never less than approximately 10 to 15 dB/cm. On the silicon wafers, the losses were worse. As will be seen later, this became a severe hindrance to the testing of the principles of wavelength-dependent coupling.

One of the requirements of these waveguiding structures is that either the buffer layer or the waveguide have a taper, so that the longer wavelengths can be coupled out at a different physical location than the shorter wavelengths. To demonstrate that tapered films can be fabricated, tapered layers of PSK2 were deposited on the silicon substrates. This was accomplished by de-centering the substrate holder above the sputtering target. The substrates were held off-center, and thus the end of the substrate closer to the center of the target had thicker layers deposited than the portion of the substrate farther away from the target. This procedure produced nicely uniform tapers. The taper was visible to the eye as a series of interference fringes across the film. Also, by measuring the guided-mode indices of the film, and fitting the observed β values to the β values calculated by the computer program, the thickness and index of the guiding layer can be estimated. The thicknesses at either end of the film were indeed found to be different, with tapers of about 1/2 μm over a length of 40 mm being typical.

To characterize the waveguides, a method to couple into the guides was required. Since it was felt that the pressure of prism coupling into the guides would crack them, grating couplers were used. A photoresist grating was written on the surface of the waveguide using holographic techniques. By measuring the grating line spacing and the angles at which light coupled into the waveguide, the β values for the guide could be calculated. The computer program was then used to deduce the index and thickness of the guides.

The next task in the characterization of the waveguides was the measurement of the losses of the guide. To this end, a method developed by Himel and Gibson[7] was employed. When a guided mode propagates in a waveguide with scattering losses, light is scattered out of the plane of the waveguide, forming a visible streak. A coherent fiber bundle was placed in contact with the waveguide streak. A 20 μ slit was scanned across the end of the fiber bundle, and the output fed into a photomultiplier tube. The intensity seen by the photomultiplier was detected by a lock-in amplifier, collected by a microcomputer, and plotted by a data-reduction routine. The logarithms of the intensity values were taken and displayed by the computer. If the intensity decay is an exponential function of length, then the logarithm is a linear function of length, with the slope equal to the loss coefficient. A linear regression best-fit routine was used to fit the line to determine this coefficient. The loss values were read from the linear fit.

Results

The results of the experiments are tabulated in Tables 1 through 3, and also in the accompanying graphs. The measured and the calculated values of the effective index (equal to β_r) and the losses (proportional to β_i) are shown. When no experimental value is entered in the table, the measurement could not be made, for reasons explained below. As can be seen, the agreement between theory and experiment for β_r is quite good, while for β_i it is not as good. This has several explanations.

The root of the problem is the extremely poor quality of the waveguides. The loss-measurement technique requires a visible streak extending over several millimeters. As the streak gets shorter, the accuracy of the technique is reduced. Also, experimentally, as the losses increase, the intensity of the streak weakens, and the signal-to-noise ratio of the experiment worsens. For many of the lossier higher-order modes, the streak was only a few millimeters long. The error involved in fitting a best-fit line to such a short streak is quite large, as much as ±50%. Thus, for losses above 30 to 40 dB/cm, very accurate measurements cannot be expected.

However, this does not explain why the losses in the measurable modes were found to be almost constant. A possible explanation is that in the presence of high scattering losses, as Marcuse has shown,[8] the power in a waveguide distributes itself among all the modes of the guide. So, in our samples, optical power is probably being scattered from the mode of interest into lower-order modes. These modes all have approximately the same losses. A rough calculation from Marcuse shows that for a 30 dB/cm waveguide, the steady-state power distribution should be reached after about 0.2 to 2 mm, depending on the correlation length of the refractive index inhomogenieties that generate the scattering. The distance from the grating coupler to the edge of the fiber bundle was typically on the order of 1 mm, so the experiment was always performed in the steady-state power distribution region. In Marcuse's words, ". . . once the steady state is reached, the average power carried by each mode decreases at the same rate . . . ."[9] Thus the losses appear to be almost the same as in the lower-order modes. For the very high-order modes, where theory predicts losses in excess of 100 dB/cm, the optical power is absorbed by the silicon before it has a chance to scatter into the lower-order modes. Thus there is essentially no streak, and no way to make a measurement of the losses. So the higher-order modes do have extremely high losses, as expected.

It appears that we have verified Marcuse's coupled-power theory more thoroughly than we have demonstrated wavelength-dependent coupling. However, we did see that the higher-order modes have extremely high losses, as predicted by the theory. Also, since such good agreement for the real part of the propagation constant was seen, it follows that the imaginary part (which deals with losses) should agree with experiment as well. Both derive from the same complex solution of Maxwell's equations, which are quite sound. We are confident that with adequate waveguides, the theory would be shown to be accurate.

Table 1. Effective indices and losses for Sample One. SiO_2 buffer layer thickness is 0.256 μ.

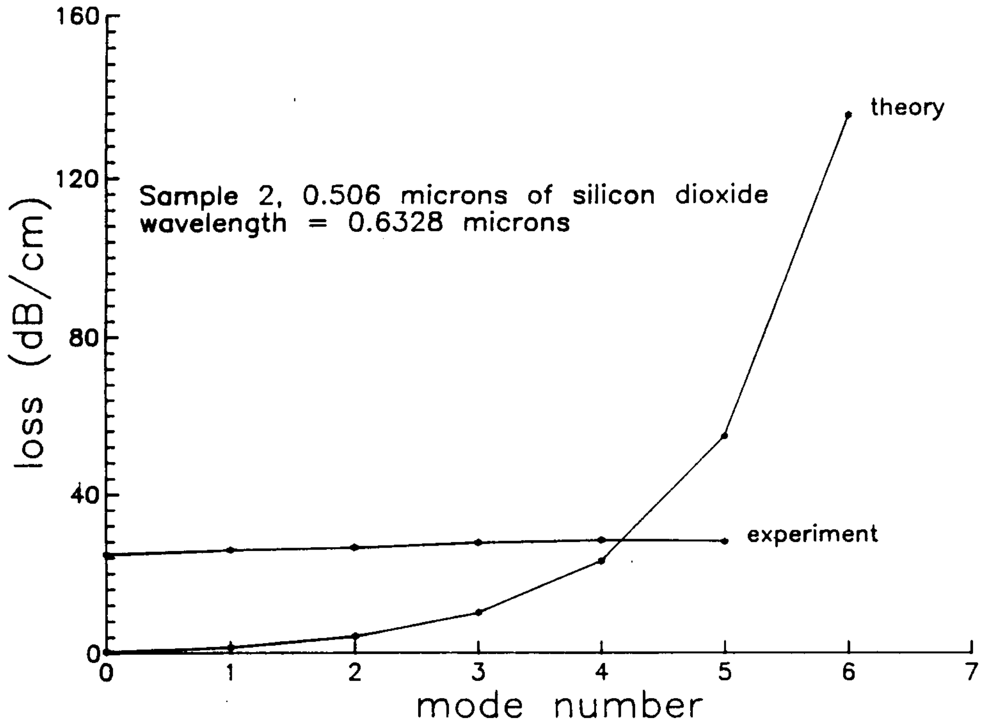
Mode Number	THEORY N_{eff}	THEORY loss (dB/cm)	EXPERIMENT N_{eff}	EXPERIMENT loss (dB/cm)
Wavelength = 0.6328 μ				
0	1.5619	9.202	1.5620	34.12
1	1.5524	38.69	1.5523	36.08
2	1.5366	94.53	1.5361	34.5
3	1.5142	188	1.5152	
4	1.4850	340	1.4851	
Wavelength = 0.532 μ				
0	1.5657	3.86	1.5657	35.2
1	1.5589	16.26	1.5600	36.5
2	1.5476	39.9	1.5483	37.7
3	1.5316	79.9	1.5334	37.1
4	1.5108	145	1.5131	
5	1.4852	253		
6	1.4546	428		

Table 2. Effective indices and losses for Sample Two. SiO_2 buffer layer thickness is 0.506 μ.

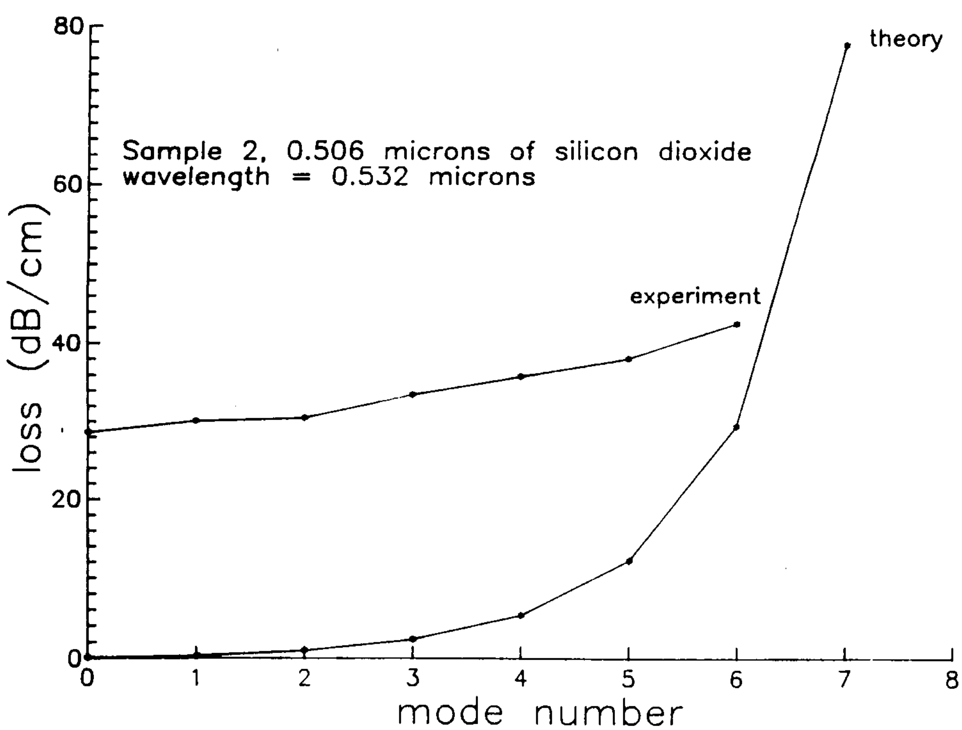
Mode Number	THEORY N_{eff}	THEORY loss (dB/cm)	EXPERIMENT N_{eff}	EXPERIMENT loss (dB/cm)
Wavelength = 0.6328 μ				
0	1.5628	0.34	1.5629	24.8
1	1.5563	1.53	1.5554	25.9
2	1.5454	4.23	1.5461	26.5
3	1.5301	10.1	1.5297	27.7
4	1.5103	23.1	1.5110	28.3
5	1.4860	54.4	1.4852	27.9
6	1.4573	135	1.4558	
Wavelength = 0.532 μ				
0	1.5664	0.083	1.5679	28.6
1	1.5617	0.373	1.5637	30.1
2	1.5539	1.01	1.5548	30.5
3	1.5429	2.37	1.5433	33.5
4	1.5287	5.30	1.5273	35.8
5	1.5112	12.1	1.5084	38.0
6	1.4906	29.3	1.4878	42.5
7	1.4668	77.5	1.4606	

Table 3. Effective indices and losses for Sample Three. SiO_2 buffer layer thickness is 0.74 μ.

Mode Number	THEORY N_{eff}	THEORY loss (dB/cm)	EXPERIMENT N_{eff}	EXPERIMENT loss (dB/cm)
Wavelength = 0.6328 μ				
0	1.5615	0.031	1.5613	27.7
1	1.5542	0.154	1.5537	21.7
2	1.5418	0.515	1.5419	23.2
3	1.5245	1.64	1.5250	30.9
4	1.5022	5.73	1.5030	33.1
5	1.4751	24.3	1.4768	39.4
Wavelength = 0.532 μ				
0	1.5652	0.005	1.5660	23.9
1	1.5599	0.023	1.5605	27.0
2	1.5510	0.075	1.5528	26.9
3	1.5385	0.224	1.5409	29.1
4	1.5224	0.711	1.5242	31.0
5	1.5027	2.63	1.5062	32.5
6	1.4796	12.48	1.4841	



160
120
80
40
0
0
1
2
3
4
5
6
7
loss (dB/cm)
mode number
Sample 2, 0.506 microns of silicon dioxide
wavelength = 0.6328 microns
theory
experiment



80
60
40
20
0
0
1
2
3
4
5
6
7
8
loss (dB/cm)
mode number
Sample 2, 0.506 microns of silicon dioxide
wavelength = 0.532 microns
theory
experiment

References

1. G. I. Stegeman, J. J. Burke, and D. G. Hall, "Surface-polariton-like waves guided by thin, lossy metal films," Opt. Lett. **8**, 383 (1983).

2. G. I. Stegeman and J. J. Burke, "Long-range surface plasmons in electrode structures," Appl. Phys. Lett. **43**, 221 (1983).

3. G. I. Stegeman and J. J. Burke, "Effects of gaps on long-range surface plasmon polaritons," J. Appl. Phys. **54**, 4481 (1983).

4. J. J. Burke, G. I. Stegeman, and T. Tamir, "Surface polariton-like waves guided by thin, lossy metal films," Phys. Rev. B **33**, 5186 (1986).

5. J. Chilwell and I. Hodgkinson, "Thin films field-transfer matrix theory of planar multilayer waveguides and reflection from prism loaded guides," J. Opt. Soc. Am. A, **1**, 742 (1984).

6. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, New York, 1980), pp. 51-70.

7. M. D. Himel and U. J. Gibson, "Measurement of planar waveguide losses using a coherent fiber bundle," Appl. Opt. **25**, 4413 (1986).

8. D. Marcuse, *Theory of Dielectric Waveguides* (Academic Press, New York, Academic Press, 1974), pp. 181-193.

9. Ibid, p. 184.