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CHARACTERISTICS OF SINGLE-AND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of investigations into the properties of single-mode and multi-mode optical waveguides are summarized. Specific results include propagation constants for fibers of arbitrary cross-section; an experimental study of tapers, truncations and offsets in slab waveguides; the effects of curvature on channel waveguides embedded in layered substrates; a new method for efficient computation of beams propagating in multimode waveguides; and investigation of mode coupling between multimode waveguides.

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I. Introduction

The objective of this research project was to investigate propagation and coupling phenomena in both single-mode and multimode optical waveguides. The goals included characterization of several important canonical problems whose solutions are essential to the design of complex systems involving both single-mode and multimode guides:

a) the transformation of rays and beams in a multimode waveguide;

b) the radiation and scattering from a taper or angle cut in a waveguide;

c) characterization of the modes of a multimode waveguide of arbitrary cross-section;

d) coupling of multimode waveguides;

e) curvature effects in integrated optical waveguides.

In the following section, we summarize the specific results of this research program. This is followed by a lsit of publications and a statement of personnel participating in the project.

II. Results of the Research Project

A) Study of modes of arbitrarily-shaped optical fibers

Based upon an integral-equation formulation, we have obtained an accurate method for obtaining the propagation constant of the fundamental mode of an optical fiber of any shape, so long as only this fundamental mode can propagate. In this range, the mode fields are linearly-polarized and vary only a little over the core of the fiber. The area of the core, its geometric mean radius, and higher-order moments characterizing its shape are all that are needed to evaluate the propagation constant. Details are given in [1], [4] and [9].

Far from cutoff, the modes of an arbitrarily-shaped fiber have their fields highly concentrated in the core region, and their functional dependence on the transverse coordinates resembles that of the E_z field of a TM mode in a hollow metallic waveguide of the same cross-sectional shape. Using this knowledge in the integral equation mentioned above, we can obtain approximate but closed-form equations for the propagation constants of the fiber in the high-frequency limit. These are very accurate in the case of a multimode waveguide when most of the modes are far above cutoff, but also give fair accuracy (10 or 20 percent) at quite low frequencies as well. The formulas obtained can thus be used when a rough estimate of the propagation characteristics of an arbitrary fiber is needed. This work has been reported in [10].

B. Experimental study of discontinuities in dielectric waveguides

Only the simplest discontinuities in optical waveguides are easily analyzed theoretically. Many important types of irregularities in these guides have no adequate theory to describe their reflection, transmission, and scattering properties. An experimental study was thus made of several such irregularities in a dielectric waveguide. To ease fabrication tolerances and make best use of existing facilities, the experiments were conducted on slab configurations at microwave frequencies. The radiation from abruptly and gradually truncated (tapered) slabs was measured as well as the coupling between two such truncated waveguides separated by gaps and offsets of the axis. A certain amount of "pulling" of the surface wave field in the direction of the taper was evident, but the effect of tapers and offsets on the radiation patterns and transmission factor appeared to be more subtle, and in a few cases contradictory to one's intuitive expectations. These results point to the need for a more complete theoretical understanding of these configurations, if useful design information is to be available. This work has been presented in [5] and [11].

C. Study of substrate effects on curvature loss of channel waveguides

It is known that optical waveguides with homogeneous cladding suffer attenuation due to radiation losses when the axis of the guide is uniformly curved. The physical mechanism is a continuous "shedding" of rays tangentially from a so-called caustic located outside of and in the plane of the curved guide. The attenuation constant in this case has the form $c_1 R^{-1/2} \exp(-c_2 R)$, where c_1 and c_2 are constants and R is the radius of curvature of the guide. A study was made of the influence of a substrate on this radiation loss. It was found that a substantial cancellation of this radiation occurs when the substrate in which the curved guide is embedded is very dense electrically by comparison with the region above the substrate. The resulting attenuation constant has the form $c_3 R^{-3/2} \exp(-c_4 R)$, and can be an order of magnitude smaller than that of a comparable bent guide with homogeneous cladding. We have consolidated these findings into an overall physical picture of the radiation loss mechanism in curved open waveguides in the presence of stratified media. For details, see [6], [12], [13] and [14].

D. Beam propagation in multimode waveguides

A powerful new method for studying the propagation of Gaussian beams in multimode optical waveguides has been developed and applied to several important optical waveguide configurations. The approach is based on the Fourier/Fresnel imaging phenomenon in these waveguides: a field pattern imposed at $z = 0$ is (in the paraxial approximation) replicated at the planes $z = z_{11}, 2z_{11}, 3z_{11}$, etc., where z_{11} is a characteristic imaging distance. Somewhat more complicated rearrangements of the input field pattern appear at $z = (p/q)z_{11}$, where p and q are integers. When the input pattern is that of a Gaussian beam, we can interpolate between these image planes by allowing the beam to broaden as it would in an infinite homogeneous region. The results of computation according to this method compare well with computationally much more expensive mode summations. For typical optical waveguides, the method remains accurate for lengths of up to a few tens of meters. A first-order correction has been obtained which extends this accuracy out to lengths of a kilometer or so. The development of the basic theory is contained in [2], [7], [15], [16], [17] and [18].

This technique was extended to the case of two identical parallel slab-waveguides which are coupled through their cladding fields. It was found that complete power transfer (which is possible for a pair of single-mode guides) is possible only under certain conditions, and that a very complex process of power transfer between the two slabs exists. The coupling and imaging processes in the two guides can serve to form identical images in either guide, or split the beam at the output so that a single device might serve as directional coupler, beam splitter, optical switch, etc. As in the case of a single guide, computation of coupled guides using this approach is highly efficient. This research is published in [3], [8] and [19].

Under development at the time of expiration of the grant was the adaptation of the technique to multimode circular optical fibers. This expression has proved more challenging than was first anticipated, and the adaptation has been only partially successful. The complications introduced by the cylindrical geometry are that the waveguide produces a certain kind of transform of the input field, as well as an image of the input field itself. This work has not yet been completed or reported, but this is expected in the near future.

An experiment was devised (using the microwave modelling technique described in (B) above) to verify the self-imaging theory for slab waveguides. Because of the difficulty of obtaining a clean input field distribution, the verification was not achieved for high-order multiple images, but low-order images appeared to be in good agreement with the theory. This formed the subject of a M.S. thesis by Mr. T. Pett (see section V).

In summary, this investigation has focused on a variety of optical waveguide properties, related both to single-mode and multimode propagation. The most important result has been the hybrid analysis method of beam propagation in multimode waveguides. This study has only scratched the surface of this technique, and it remains for future investigations to fully exploit its potential.

III. List of Publications

A. Papers published in the open literature

[1] E.F. Kuester and R.C. Pate, "Fundamental mode propagation on dielectric fibres of arbitrary cross-section," IEE Proc. vol. 127, part H, pp. 41-51 (1980).

[2] D.C. Chang and E.F. Kuester, "A hybrid method for paraxial beam propagation in multimode optical waveguides," IEEE Trans. Micr. Theory Tech., vol. 29, pp. 923-933 (1981).

[3] E.F. Kuester, G.S. Dow and D.C. Chang, "Coupling and imaging of Gaussian beams in parallel dielectric slab waveguides," AEÜ, accepted for publication, 1982.

B. Technical Reports

[4] R.C. Pate and E.F. Kuester, "Fundamental propagation modes on a dielectric waveguide of arbitrary cross section," Sci. Rept. No. 45, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colorado, Boulder, 1979.

[5] R.F. German, "Microwave model of a dielectric slab waveguide," Sci. Rept. No. 68, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colorado, Boulder, 1981.

[6] E.F. Kuester, R.L. Holland and D.C. Chang, "Radiation loss from a curved dielectric channel waveguide in a dense substrate," Sci . Rept. No. 64, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colorado, Boulder, 1981.

[7] D.C. Chang and E.F. Kuester, "A hybrid method for paraxial beam propagation in multimode optical waveguides," Sci. Rept. No. 54, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colorado, Boulder, 1980.

[8] G.S. Dow, "Imaging and coupling of two parallel slab waveguides," Sci. Rept. No. 62, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colorado, Boulder, 1981.

C. Conference presentations

[9] E.F. Kuester and R.C. Pate, "Fundamental mode propagation on dielectric fibers of some noncircular cross sections," IEEE MTT-S International Microwave Symposium, 30 April - 2 May 1979, Orlando, FL, pp. 475-477.

[10] E.F. Kuester and R. Ebrahimian, "Propagation constants for step-index fibers of arbitrary cross-section at high frequency," USNC/URSI National Radio Science Meeting, 16-19 June 1981, Los Angeles, CA, p. 33.

[11] R. German, E.F. Kuester and D.C. Chang, "Experimental investigation of surface wave radiation from a tapered dielectric slab," USNC/URSI National Radio Science Meeting, 5-8 November 1979, Boulder, CO, p.92.

[12] E.F. Kuester, D.C. Chang and R.L. Holland, "The radiation loss of a curved dielectric channel waveguide near a dielectric interface," USNC/URSI National Radio Science Meeting, 12-16 January, 1981, Boulder, CO, p. 157.

[13] E.F. Kuester, "Bending losses of open waveguides," USNC/URSI National Radio Science Meeting, 16-19 June 1981, Los Angeles, CA, p. 47.

[14] D.C. Chang, E.F. Kuester and R.L. Holland, "Bending loss of a dielectric channel waveguide," SPIE Topical Meeting on Microwave, Millimeter and Optical Integrated Circuits, November 1981, Huntsville, AL.

[15] D.C. Chang, E.F. Kuester and S. Nakayama, "A hybrid representation for optical wave propagation in an over-moded slab dielectric waveguide," USNC/URSI National Radio Science Meeting, 5-8 November 1979, Boulder, CO, p. 131.

[16] E.F. Kuester and D.C. Chang, "A hybrid method for paraxial beam propagation in multimode waveguides," IEEE MTT-S International Microwave Symposium, 28-30 May 1980, Washington, D.C., pp. 456-458.

[17] E.F. Kuester and D.C. Chang, "First-order corrections to expressions for paraxial beam propagation in multimode parallel-plate or dielectric-slab waveguides," URSI North American Radio Science Meeting, 2-6 June 1980, Quebec, Canada, p. 113.

[18] D.C. Chang and E.F. Kuester, "Optical propagation in an over-moded dielectric guide," URSI International Symposium, 26-29 August 1980, Munich, Germany, pp. 315B/1-315B/4.

[19] E.F. Kuester, S.Dow and D.C. Chang, "Imaging and coupling in parallel multimode dielectric slab waveguides," SPIE Conference on Guided-Wave Optical and Surface Acoustic Wave Devices, Systems, and Applications, 29-31 July 1980, San Diego, CA, pp. 80-83.

IV. Personnel Participating in the Research

1. Dr. David C. Chang, Professor (Electrical Engineering)
2. Dr. Edward F. Kuester, Associate Professor (Electrical Engineering)
3. Dr. Samuel W. Maley, Professor (Electrical Engineering
4. Mr. Ronald C. Pate, graduate student (M.S., 1979).
5. Mr. Robert F. German, graduate student (M.S., 1981)
6. Mr. S. Nakayama, graduate student, M.S. (summer, 1979).
7. Mr. Robert L. Holland, graduate student and research assistant (8/14/79 - 11/30/81) (Ph.D., in progress).
8. Mr. G. S. Dow, graduate student and research assistant (2/15/80-8/19/80) (M.S., 1981).
9. Ms. Rozalina Ebrahimian, graduate student and research assistant (1/15/81 - 5/30/81) (M.S., in progress)
10. Mr. Todd Pett, graduate student and research assistant (1/17/80-9/30/80) (M.S., 1981).
11. Mr. Ali R. Mahnad, graduate student and research assistant (2/1/80 - 8/25/81) (M.S. in progress).

V. List of Theses

1. "Imaging and coupling of two parallel slab waveguides," M.Sc. Thesis, by G. Samuel Dow, January 1981.

2. "Solution of fundamental propagation nodes on dielectric waveguide of arbitrary cross section," M. Sc. Thesis, by Ronald C. Pate, December, 1979.

3. "Microwave model of a dielectric slab waveguide," M.Sc. Thesis, by Robert F. German, December, 1979.

4. "Experimental investigation of Fresnel imaging in a dielectric slab waveguide," M.Sc. Thesis, by Todd A. Pett, December, 1981.

In addition, we expect shortly the completion of masters' theses on optical waveguide topics by Ali Mahnad and Rozalina Ebrahimian. A Ph.D. dissertation by Robert L. Holland which deals in part with curvature of channel waveguides is currently in progress.