SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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Field	Entry
1. REPORT NUMBER	
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	Studies of Non-Reciprocal Effects in Planar Submillimeter to Optical Waveguiding Structures and of Monolithic Circuits
5. TYPE OF REPORT & PERIOD COVERED	Final
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	T. Itoh
8. CONTRACT OR GRANT NUMBER(s)	N00014-79-C-0553
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Dept. of Electrical & Computer Engineering The University of Texas Austin, TX 78712
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
11. CONTROLLING OFFICE NAME AND ADDRESS	
12. REPORT DATE	October 19, 1988
13. NUMBER OF PAGES	11
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	
15. SECURITY CLASS. (of this report)	
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nonreciprocal structure, isolator, dielectric waveguide, printed transmission lines, monolithic microwave integrated circuits, slow wave structures, semiconductor substrate, Schottky contact, MIS structure, microwave integrated circuits, millimeter-wave integrated circuits, complex modes, stripline crossing, strip-to-slot transition, coplanar waveguide, open microstrip resonator, (cont'd.)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes technical activities and accomplishments under the support from the Office of Naval Research in the area of waveguiding structures for nonreciprocal devices, monolithic integrated circuits and related subjects. The report is divided into three parts. First, a number of nonreciprocal open waveguiding structures analyzed in this project are summarized. Second, an effort to characterize printed transmission lines formed on a semiconductor substrate containing a lossy layer is reported. The third part summarizes a number of approaches to characterize discontinuities in a printed transmission line. (cont'd)

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S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. Key Words cont'd.
time-domain method of lines, superconductor

20. Abstract cont'd.
In addition, a preliminary effort for investigation of a transmission line suited for high critical temperature superconductors is presented.

OFFICE OF NAVAL RESEARCH

FINAL TECHNICAL REPORT

FOR

TASK NO. NR 371-012

CONTRACT N00014-79-C-0553

STUDIES OF NON-RECIPROCAL EFFECTS IN PLANAR SUBMILLIMETER TO OPTICAL WAVEGUIDING STRUCTURES AND OF MONOLITHIC CIRCUITS

OCTOBER 19, 1988

BY

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Abstract

This report summarizes technical activities and accomplishment under the support from Office of Naval Research in the area of waveguiding structures for nonreciprocal devices, monolithic integrated circuits and related subjects. The report is divided into three parts. First, a number of nonreciprocal open waveguiding structures analyzed in this project are summarized. Second, an effort to characterizing printed transmission lines formed on a semiconductor substrate containing a lossy layer is reported. The third part summarizes a number of approaches to characterize discontinuities in a printed transmission line. In addition, a preliminary effort for investigation of a transmission line suited for high critical temperature superconductors is presented.

Introduction

As the operating frequency is increased, wave interactions in a microwave circuit become significant. The guided wave characteristics are affected both by the materials in the structures and the structural configurations. Clear understanding of the guided wave characteristics in these environments is essential before any high frequency microwave and millimeter-wave circuits are designed and constructed. The problems attacked under the support of this contract have been chosen and analyzed with this background.

Nonreciprocal Guided Wave Structures

Understanding of field displacement type nonreciprocal wave phenomena in an open waveguide structure is important for developement of nonreciprocal devices at higher microwave and millimeter-wave circuits. For several promising planar and quasi-planar structures, qualitative and quantitative studies have been conducted. The first structure studied is a distributed isolator made of nonreciprocal leakage phenomena provided by grating elements placed on a nonsymmetric open waveguide containing a gyrotropic slab layer. In such a waveguide, the transverse field distribution is shifted into one lateral direction depending on the direction of propagation. Due to the structural nonsymmetry, these shifted waves see different material environment and, hence, their propagation constants are different. Now, if the period of the grating is chosen in such a way that the wave propagating in one direction enters the leaky wave region whereas the one in the opposite direction is still in the surface wave region, then the former attenuates due to leakage as it propagates. On the other hand, the latter is not significantly affected. Hence, an isolator action takes place. An analytical and experimental study was done by using a ferrite loaded dielectric waveguide with grooved grating elements. The expeiments at X band confirmed the theoretical prediction by a grating made of metal strips. Hence, the structure is amenable for accurate analysis based on the spectral domain method.

The next problem attacked was to find an open gyrotropic waveguide in which nonreciprocity is maximized. An optimum three layer structure was found by the transverse resonance technique.

The third problem was a distributed isolator and circulator for frequency of operation around 200 GHz. These structures are made of open gyrotropic waveguide and an isotropic waveguide which are coupled by a proximity effect. The propagation constant of the isotropic waveguide is chosen close to that of the guided wave in a particular direction band confirmed the theoretical prediction by a grating made of metal strips. Hence, the structure is amenable for accurate analysis based on the spectral domain method.

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The third problem was a distributed isolator and circulator for frequency of operation around 200 GHz. These structures are made of open gyrotropic waveguide and an isotropic waveguide which are coupled by a proximity effect. The propagation constant of the isotropic waveguide is chosen close to that of the guided wave in a particular direction in the gyrotropic waveguide. Hence, the coupling between the waveguides takes place only for the wave propagating in one direction but not in another direction. Hence, the nonreciprocal action can be realized. These structures have been analyzed by a coupled-mode theory and a number of design data have been generated. Subsequently, a more accurate analysis technique based on the transverse resonance method has been implemented. An experimental test of the structure was carried out at 35 GHz. The theoretical results and the experimental findings agree well.

Another nonreciprocal structure was studied by the use of two dielectric waveguides coupled by a ferrite overlay. The entire structure looks like a hollow image guide. By applying the magnetic bias in the horizontal direction, the waves traveling in the opposite directions are shifted upward and downward and, hence, the coupling properties between the two dielectric waveguides are direction dependent. This mechanism can be used for realization of nonreciprocal phenomena. A prototype structure was designed and built for 35 GHz operation. The experimental results agreed well with the theoretical prediction.

Printed Transmission Lines on a Semiconductor Substrate

In a monolithic microwave integrated circuit, a printed transmission line is ordinarily formed on a semi-insulated substrate. In such structures, the analysis of transmission lines is carried out under the assumption that the substrate is lossless and then use a perturbation analysis to estimate the attenuation caused by the imperfect conductor and dielectric. However, there is a class of printed transmission lines known as a slow wave structure. This structure is formed by a printed transmission line placed on a semiconductor substrate which contains a lossy region below the conductor via a thin lossless layer. Depending on the structural and material parameters and the operating frequency, the modal field in such a transmission line can be one of the following three: skin effect mode, lossy dielectric mode and slow wave mode. The slow wave mode is an intermediate situation between two others. In such a situation, the magnetic field distribution is affected very little by the lossy layer whereas the electric field tends to concentrate in the lossless layer immediately below the conductor. Therefore, there is a substantial spatial separation of electric and magnetic fields. Since the capacitance per unit length increases, the phase velocity decreases significantly. There are two different constructions to attain this slow wave mechanism. One is to use an MIS (Metal Insulator Semiconductor) configuration and another is to use a Schottky contacted electrode. In the latter case, the doped region immediately below the conductor is depleted so that a thin insulating region is created. It should be noted that the slow wave mechanism is generated by the presence of a lossy layer. Hence, the configuration is fundamentally lossy. However, one of the attractive features of these structures is that the guide wavelength along can be substantially reduced, e.g. up to 5% of the free space wavelength. Hence, for a given electrical length required for a passive structure, the physical length is very small. Thus, a substantial savings in real estate on a semiconductor substrate such as the one used in a monolithic integrated circuit can be realized. It is important, however, to study the phase velocity and the attenuation in these slow wave structures so that their viability for miniaturized passive components is found out.

These slow wave structures have been extensively analyzed under this contract. Several numerical techniques including the spectral domain method and the mode matching method have been used for characterizing the MIS and Schottky slow wave microstrip lines and coplanar waveguides. The depletion region under the Schottky contacted electrode was modeled by an insulating layer for analysis purpose.

Since the slow wave structure is fundamentally lossy, it is important to find a possible modification in which only the attenuation is reduced without degrading the slow wave factor. A periodically doped slow wave structure has been ananlyzed as a possible candidate for such a purpose. In this structure, the slow wave region and ordinary region are periodically alternating along the waveguiding direction. The periodic doping is designed to reduce the attenuation per unit physical length while the periodicity enhances the slow wave factor or at least prevents its reduction. After a number of parametric studies, it was found that for a certain combination of the material and structural parameters, it is possible to attain the objective stated above.

The problem of using the slow wave structures for high speed digital circuits was investigated. It was found that the slow wave structure is a viable candidate for high speed pulse circuit and that an appropriate set of structural and material parameters need to be chosen so that the pulse distortion is minimized. Use of these slow wave structures for an electronically tunable phase shifter has also been investigated extensively. It was found that this is viable although the change of insertion loss due to electronic bias change needs to be minimized or compensated by some means.

In the earlier analysis, the depletion region under the Schottky contacted electrode was modeled by a layered structure. In order to find if this is an acceptable approximation, a finite-element computer program was developed which can analyze a waveguide with an arbitrary cross section. It was found that the layered model is a good approximation for a microstrip configuraion whereas a substantial error may be encountered in the case of a coplanar waveguide configuration for a certain set of structural parameters.

Characterizations of Discontinuities in a Printed Transmission Lines

The analysis of discontinuities appearing in the microwave and millimeter-wave integrated circuits is one of the most difficult electromagnetic problems. However, importance of accurate analysis of such discontinuities intensifies as the operating frequency is increased. Commonly available quasi-static analysis methods no longer provide accurate information. More elaborate electromagnetic analysis methods are necessary. To this end, a number of projects have been undertaken under support of this contract.

1) Complex modes

It was recently reported that waveguide modes with a complex propagation constant can exist in a lossless closed waveguide filled inhomogeneously. These modes appear in pair and no net energy is transported. It is reported that these modes are portions of the modal spectrum and, hence, must be included in the characterization of a discontinuity by the mode matching technique. Existence of these complex modes in a closed microstrip line has been numerically confirmed.

2) Stripline crossing and strip-to-slot transmissions

In advanced microwave integrated circuits as well as in many high speed digital integrated circuits, striplines are placed along the orithogonal directions on two sides of the substrate. Hence, these lines are electromagnetically coupled. This problem has been analyzed by the new method called the transverse resonance analysis. In this method, the fields in air above the substrate, in the substrate and in air below the substrate are expanded into orthogonal sets after the stripline crossing is enclosed in a rectangular cavity. When the fields are matched at two air-dielectric interfaces, the eigenvalue equation for the resonant frequency is obtained. This entire structure can be written in terms of an equivalent circuit in which the crossing is expressed in terms of a 4 x 4 impedance matrix. Four striplines are short circuited by the rectangular box. Since the impedance matrix contain only 5 independent unknowns, we can solve the problems if we obtain five independent equations. We can accomplish this by seeking five different configurations which resonate at a given frequency. The resonance condition can be calculated from the field formulations described above. The algorithm based on this approach has been developed.

The same approach has been applied to the problem of the microstrip-to-slotline transmission. The results from this approach have been compared with the quasi-static method commonly used.

3) Coplanar waveguide discontinuities

The technique described above is being applied to characterization of various discontinuities in a coplanar waveguide. Presently, the formulation for the step discontinuity is being completed.

4) Open microstrip resonator

Characterization of an open end of the microstrip line is one of the most important electromagnetic problems associated with the microwave and millimeter-wave integrated circuits. One way to study this problem is the solution of the complex eigenvalue problem of an open microstrip resonator based on the full wave analysis. This analysis takes into account all wave aspects including the radiation and surface wave effects. The formulation of the problem is based on the spectral domain method. The solution is by way of Galerkin's technique and the complex resonant frequency is sought. The real part of the complex frequency is resonant frequency while the imaginary part accounts for the energy loss of the resonator due to radiation and surface wave excitation. An extensive study has been made on the integration path in the spectral domain in relation to the branch cut and the surface wave poles. The open microstrip resonator can be modeled by an equivalent circuit consisting of a piece of transmission line terminated on both ends with the fringing capacitance and the radiation conductance. Hence, these equivalent circuit parameters can be related to the real and imaginary parts of the complex resonant frequency.

4) Time-domain method of lines

The guided wave characteristics in a microwave and millimeter-wave integrated circuit configuration can be analyzed in the time domain as well as in the frequency domain. In most of the analyses intended for microwave applications are conducted in the frequency domain since the steady state condition is assumed. However, in a high speed digital circuit, the time domain method is more practical as the propagating pulse contains a broad frequency spectrum. The time domain approach is a broadband technique. It usually requires more computation time. However, the amount of information derived can far exceed that of the frequency domain method.

The conventional time domain method is based on the finite difference method in which the entire space of interest is divided into three-dimensional meshes. The discritized version of Maxwell's equations are solved in each time step. Hence, the amount of computational labor and storage requirements are significant. A new numerical method is proposed here which is adaptable to printed circuit structures appearing in the microwave and millimeter-wave integrated circuit. It is recognized that in these structures any discontinuities are usually located on the substrate surface. The regions above and below the substrate surface are uniform and homogeneous. Therefore, only the substrate surface containing the metalization is discretized into two dimensional meshes. Maxwell's equations are discretized only in these two dimensions. The information of the field normal to the substrate surface is analytically incorporated in the solution process. Hence, a substantial reduction in computational labor and storage requirement is expected. This method has been tested by several simple structures and the above claim is substantiated. Further development of the method will be carriied out under the forthcoming ONR support.

Preliminary Work on Superconducting Transmission Lines

Preliminary work on a printed transmission line made of a futuristic high critical temperature superconductor was initiated. It is presumed that in such an idealistic structure, the conductor loss which is the dominant loss mechanism in a convetional metal structure is no longer the dominant one, although the conductor loss in such a structure is nonzero except at the dc frequency. Hence, the important consideration of such a transmission line is reduction of dielectric loss. In this study several candidate structures of the microstrip line family have been investigated for possible dielectric loss reduction. It was found that the suspended strip line is a viable structure for such a purpose.

Personnel

The following personnel were involved in the course of this contract:

T. Itoh, Principal Investigator, Professor of Electrical Engineering

D. P. Neikirk, Associate Professor

H. Ling, Assistant Professor

R. Sorrentino, Visiting Professor (University of Rome)

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T. Uwano, Visiting Fellow (Matsushita Wireless Research Laboratory)

Y. C. Shih, Graduate Research Assistant, Ph.D. 1982

Y. Fukuoka. Graduate Reserach Assistant, Ph.D. 1984

S. W. Yun, Graduate Research Assistant, Ph.D. 1984

N. Camilleri, Graduate Research Assistant, Ph.D. 1985

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