Dielectric Guiding Structures and Applications

Shanjia Xu

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by Shanjia Xu

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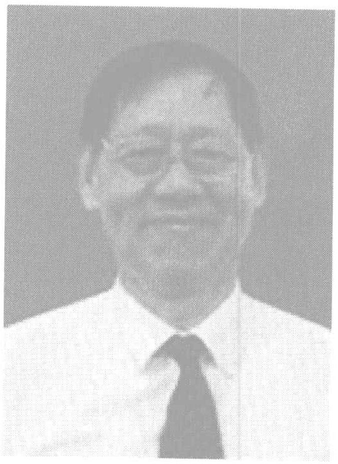
Brief Biography of Professor Shanjia Xu

Prof. Shanjia Xu was born in Zhejing, China, in 1939. He graduated from the university of Science and Technology of China (USTC) in 1965. Since then he has been with the same university. He was promoted directly from Lecturer to Professor and became associate chairman of the Department in 1986. From 1994 to 1999 he was the vice-present of High Technical College and from 1993 to 1999 he was the chairman of the Department of Electronic Engineering and Information Science. He was the vice-director of Academic Committee of USTC from 1993 to 2000.



During 1983 – 1986, he was a Visiting Scholar at the Polytechnic Institute of New York (Polytechnic University) U.S.A. From September 1991 to February 1992 and from March to August 1993 he was a visiting professor at the Wurzburg University, in Wurzburg, Germany. From June to December 1998 and June to December 2000, he was a full professor at the Research Institute of Electrical Communication, Tohoku University, in Sendai, Japan. From June to August 2004 and May to June 2005, he was a full professor at the Kyushu University, in Fukuoka, Japan. He was a visiting professor at City University of Hong Kong for 4 times. Also, he was a visiting professor or an academic visitor at several universities in the Unite States, Canada, Japan, Germany, Korea and Hong Kong. He was invited to be as an Honorary Chairman, General Chairman, Chairman of the TPC, Chairman of International Steering Committee and International Adviser Committee for many International Symposia.

Prof. Xu is a Fellow of IEEE and an academician of Academy of Science of New York. He is on the Editorial or Reviewer Board of IEEE Trans. on Microwave Theory and Techniques and several other international and Chinese academy journals. He was the vice-director of the Chinese MTT Society from 1998 to 2006, and the Sub-Associate Editor of IEEE Microwave and Guided Wave Letters from 1992 to 2002.

Prof. Xu has been engaged in research in the fields of microwave, millimeter and optical wave theory and techniques and has been participating in many research programs in cooperation with both international and domestic institutes and industrial laboratories. He received the first award for the natural science given by the Chinese Academy of Sciences; the first award for science and technology given by the Kwang-Hua Science and Technology Foundation; the second award for the natural science given by Anhui Province; the second and the third award for the science and technology advances given by the Chinese Academy of Sciences. He was also recipient of National and Provincial Medal Teacher Award in 2002. He has published over 540 papers in variety of international and domestic academic journals and conference proceedings. Among them more than 380 papers are cited in the SCI and EI index. His research interests are in the areas of dielectric guiding structures and applications, numerical techniques in electromagnetic and millimeter wave theory and technology. His biography was listed in Who's Who in the world published in the U.S.A. and in the Dictionary of International Biography published in U.K.

Preface

This collection of theses on dielectric guiding structures and applications is a summary of research achievements of about 20 projects supported respectively by the National Natural Science Foundation of China, Foundation of Ministry of Science & Technology, Foundation of Education Ministry, the National Defense Technique Council, the State Education Commission, and the Ministry of Information Industry of China etc. The research results are obtained by the faculty and graduates in the Applied Electromagnetics Laboratory in the University of Science and Technology of China. The main research interests of the laboratory lie on the studies of electromagnetic wave phenomena and applications in microwave, millimeter and optical wave engineering. Such as: wave propagation, scattering and radiation in various media and structures; new numerical and analytical methods for analyzing the wave phenomena; new antennas and guiding structures for applications in electronic engineering.

The collection of theses contains 55 papers selected among 149 papers published in the international journals. The following subjects are included in the collection:

1. Nonuniform dielectric waveguides and applications.

Open dielectric waveguides have become increasingly important in the areas of integrated optics and millimeter-wave integrated circuits. An integrated circuit may consist of various waveguiding components, which are usually interconnected by gradual transition waveguides, in order to reduce the scattering loss. Generally speaking the transition waveguides, such as a bend or curved waveguide, a taper or a junction, a transition or a coupling structure may be regarded as a nonuniform waveguide. The purpose of this investigation is to get new knowledge and better understanding for different nonuniform waveguides about the variety of phenomena associated with the leakage of guided energy and leakage-related resonate effects under appropriate circumstances and to quantify the scattering characteristics of various types of nonuniform waveguides as well as to suggest some useful guidelines for design of nonuniform dielectric structures in integrated circuits.

2. Omnidirectional antennas and other new antennas for millimeter-wave applications.

The millimeter-wave region is increasingly utilized for various systems. It has generated a need for developing new types of antennas, including omnidirectional antennas to suit the various constraints imposed by these systems. The purpose of this investigation is to create some new millimeter-wave omnidirectional antennas and leaky wave antenna structures as well as to propose some effective analysis methods to calculate the performances of the new antennas. As a result, the new type antennas can be conveniently designed and manufactured to meet the practical requirements of different systems.

3. Dielectric periodic structures and applications.

The great demand for wireless communication systems is pushing designers toward mobile communication systems within small-size transmission areas. That has spurred on a research for highly integrated, small and inexpensive components that can support this kind of infrastructure. Both in millimeter-wave and optic integrated circuits of such systems, the dielectric periodic structure has demonstrated its considerable value; and it has been widely used in filters, couplers and traveling wave antennas. The purpose of this investigation is to develop an accurate but simple approach to analyze the scattering and radiation characteristics of the dielectric periodic structures so that the design procedure of the related elements in the circuits and systems becomes convenient and easy.

4. Engineerlized method for electromagnetic field problems.

Different kinds of guiding structures play an important role in advanced electrical and communication systems. The success of these systems depends strongly on the deep understanding of the propagation and scattering properties of the guiding structures. However, in practical case, often the structures have rather complicated geometry dimensions and dielectric distributions. Therefore, sometimes it could be very difficult to solve this problem with pure field method. The purpose of this investigation is to develop some novel engineerlized method, which is characterized by combining field approach with circuit technique, such as modified multimode network method, improved perturbation method, generalized transverse resonance method, impedance transform technique and simplified mode-matching method etc., to solve the eigenvalue problems for different guiding structures so that the design procedure of the systems can be greatly simplified with getting twice the results with half the effort.

5. Design and analysis of beamforming network of communication satellite.

For frequency below X-band, a satellite beamforming network (BFN) using waveguide technology is not acceptable for space applications due to its heavy weight, volume and complexity. Recently, BFNs using rectangular coaxial line technology have been applied for the feed systems of C-band satellites. By using this technology, very compact, lightweight and low loss BFNs can be built. However, there is no analytical solution for the rectangular coaxial waveguide. The purpose of this investigation is to create a new approach for the scattering analysis of the rectangular coaxial line discontinuities and to provide effective and powerful CAD software for practical use in the BFN design. It is demonstrated theoretically and experimentally that the new approach has the generality of the finite element method and the simplicity of the multimode network method while retaining the high accuracy of the mode-matching method.

6. Edge-element method and its applications.

The functional formulation with full magnetic vector is widely used to rigorously evaluate propagation problems of different complicated guiding structures filled with isotropic or anisotropic materials. The most serious problem associate with this approach is the appearance of the spurious solutions. It is verified by some authors that the edge-element method is one of the most effective ways to eliminate the spurious solutions. However, comparison with the conventional finite element method, the edge-element method is not so mature and perfect either in mathematics or in the practice. The purpose of this investigation is to bring up the criterions for space construction of the edge-element and to propose new efficient high-order mixed edge-element structure as well as to establish smart division techniques for practical applications in computations of electromagnetic field problems.

7. Theoretical and experimental investigations on leaky wave mechanism and radiation characteristics of dielectric discontinuous structures

Recently, the leakage problem has become increasingly important in electronic engineering. The purpose of this study is to find new leakage phenomenon introduced by the dielectric discontinuous structures and to post the physical essential of the phenomenon. The emphasis is laid on discussion on physical mechanism and working principle of leakage. Through intensive understanding and correct master of the leaky mechanism to precisely answer how to utilize and suppress the leakage in different circumstances and to scientifically propose the guiding principle for producing new leaky wave antenna with higher efficiency and to pursue an effective way to suppress the interference caused by the leakage in the integrated systems. Also, different methods for suppressing the interferences between the integrated circuits caused by leaky effect are effectively developed. New leaky wave antennas that are the hybrid structure of NRD guide, groove guide and microstrip line are presented. Obviously, no matter the utilization or suppression of the leakage, the study of the leaky mechanism is fundamental and pivotal; therefore the investigation of this problem is of important scientific and practical significance.

8. Left-handed Materials and Applications

Recently, left-handed materials(LHMs) with simultaneously negative permittivity ε and permeability μ, have received substantial attention in the scientific and engineering communities. Science magazine even named LHMs as one of the top ten scientific breakthroughs of 2003. Therefore, the research of LHMs is a scientific frontier in the area of physics and electromagnetics, which is still in the rapid progress. The unique properties of LHMs have allowed novel applications, concepts, and devices to be developed. In this investigation, the focus is laid on the principal theory and the application research of the LHM. The fundamental electromagnetic properties of LHMs and the physical realization of these materials are studied based on a general transmission line (TL) approach, which provides insight into the physical phenomena of LHMs and provides an efficient design tool for LH applications. LHMs are considered to be a more general model of composite right/left hand (CRLH) structures, which also include right-handed (RH) effects that occur naturally in practical LHMs. Characterization, design, and implementation of one-dimensional and two-dimensional CRLH TLs are examined, novel microwave devices based on CRLH TLs and their applications are presented. In addition, the scattering characteristics of discontinuities in LH waveguides, the propagation properties of LH periodic structures and the radiation performances of leaky wave antennas consisted of LHMs are carefully analyzed.

This collection of theses is wealth in common of our group, including all my students who made important contributions to the research achievements. Therefore, I would like to take this opportunity to express my sincere thanks to them for their offering to the research work and active help related with the collection. Particularly, I would name: F. L. Liu, L. Yang, W. D. Chen, Y. S. Xu, Q. Zhu, Y. M. Pan, M. Huang, W. H. Fang, Z. X. Zhang, C. Y. Yin, Y. F. Sun, C. Y. Wei, Z. P. Chen, X. Q. Sheng, Z. W. Ma, L.G. Sun, X. Y. Zeng, X. Z. Wu, D. Jiao, Y. Wang, J. Liu, J. F. Chen, W. H. Li, J. F. Dong, H. Z. Jing, K. H. Lin, P. Zhou, L. J. Zhang, E. Zhou, J. Zhao, W. W. Shu, S. B. Dong, Q. F. Jiang, J. H. Ming, L. J. Yin, Y. J. Zhang, K. Du, F. Wang, L. Y. You, X. K. Kuo, D. Y. Jia, Y. Z. Lin, X. B. Wang, J, Cheng, Y. Li, S. N. Wang, K. Y. Mao, F. C. Yin, Z. Z. Wu, Q. L. Xu, S. J. Fan etc.

Many thanks also to my wife for her continual sport to my reseach work and taking good care of my health and almost all family chores. I wish the publication of this collection could partly pay back my indebtedness to her.

This collection of theses is designed for use as the reference material for the graduate course "Dielectric Guiding Structures and Applications". Also, the collection provides an introduction to the people who are interested in the related field and a complete published paper list of our group is given at the end of the collection for your reference in detail. Hopefully, it is useful for your further study.

At last but not the least, the comments and the suggestions from readers would be very much appreciated.

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CONTENTS

Chapter I Nonuniform Dielectric Waveguides and Applications

Open dielectric waveguides have become increasingly important in the areas of integrated optics and millimeter-wave integrated circuits. An integrated circuit may consist of various waveguiding components, which are usually interconnected by gradual transition waveguides, in order to reduce the scattering loss. Generally speaking the transition waveguides, such as a bend or curved waveguide, a taper or a junction, a transition or a coupling structure may be regarded as a nonuniform waveguide. The purpose of this investigation is to get new knowledge and better understanding for different nonuniform waveguides about the variety of phenomena associated with the leakage of guided energy and leakage-related resonate effects under appropriate circumstances and to quantify the scattering characteristics of various types of nonuniform waveguides as well as to suggest some useful guidelines for design of nonuniform dielectric structures in integrated circuits.

In this chapter we mainly study the effect of transition waveguides on dielectric waveguide directional couplers, transitions in open millimetre-wave waveguides, substrate-mounted NRD guide for low-loss millimeter-wave integrated circuits, analysis of coupling between two parallel dielectric waveguides, network analysis of eigenvalue problem for multilayer dielectric waveguide consisting of arbitrary number of layers, E-plane waveguide filters with partially filled dielectrics for wide bandwidth and mode matching analysis of propagation characteristics for dielectric ridged guide with triangular and trapezoidal profiles.

Effect of Transition Waveguides on Dielectric Waveguide Directional Couplers

S. J. Xu[1], S. T. Peng[2], and F. K. Schwering[3]

Abstract: The coupling of energy between two curved dielectric waveguides is investigated by the staircase approximation method, which combines the building block approach of multimode network theory with a rigorous mode-matching procedure. Particular attention is directed toward two major effects of transition waveguides on the performance of directional couplers composed of dielectric waveguides: one is the change in the coupling length, the other is the radiation loss. The coupling problem is analyzed in terms of the scattering of an incident guided mode by the coupler structure as a whole. Numerical results are given to illustrate the coupling characteristics of various structures and to establish useful guidelines for the design of directional couplers.

1. Introduction

The problem of energy coupling between two parallel uniform dielectric waveguides with transition regions has been investigated in the literature. Because of the open nature of dielectric waveguides, a directional coupler requires that the input/output waveguides be kept at a distance to be isolated from each other, while a region of relatively strong coupling is provided with two waveguides sufficiently close to each other. Thus, it is necessary to introduce transition waveguides to connect the input/output waveguides with the coupling region[1]. The main purpose of the transition region is to provide a smooth flow of energy from the input/output waveguide region into the coupling region, or vice versa. Intuitively, it is expected that the transition regions should be as gradual as possible, so that the scattering losses can be reduced. On the other hand, the length of the transition regions may be limited in an integrated circuit environment, and it is necessary to determine the effect of the transition on the general scattering characteristics of the system. Also, the transition regions may provide additional coupling and it is important to assess their effect in order to establish an effective coupling length of the directional coupler as a whole.

Because of the mathematical difficulties involved in an analysis of a curved waveguide, particularly of the open type, the effect of the transition waveguides has been considered under restrictive conditions. In the past, it has been commonly assumed that the transition length is sufficiently large, so that the radiation and scattering effect caused by the curved structures can be neglected; certain analyses did not even consider the end effect or the reflection and directivity caused by coupling in the curved sections.

We present an analysis of the effect of the transition waveguides from the viewpoint of guided mode scattering by a nonuniform coupler structure. Such a method has been shown to be particularly powerful for determining the effect of the transition profile. In this analysis, two approximations are introduced. One is the staircase approximation of the continuous transition profile; this is a discretization in geometry. Evidently, in the limit of vanishing step size the piecewise-constant profile will approach the continuous one. Another approximation is an enclosure of the whole structure inside an oversize parallel-plate waveguide, so that the modal spectrum is discretized to

 IEEE Trans. on MTT 37(4): 686-690, 1989.

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facilitate the analysis. With such approximations, the mathematical analysis and the physical interpretation of wave phenomena associated with nonuniform dielectric waveguides can be kept simple and clear. It should be stressed that although the discretization of modes does introduce some degree of approximation. as far as the surface waves are concerned, the presence of an oversize parallel-plate waveguide does not change the physics of the problem.

With the piecewise-constant profile the structure can be viewed as consisting of uniform waveguides and junctions. The fields can be represented by the complete set of waveguide modes for each uniform region and are then required to satisfy the boundary conditions at each junction. The method of mode matching is then employed to solve the scattering problem including not only the fundamental mode of interest but also the effect of all the higher order modes.

Since the variation of the scattered power of the fundamental mode, including the reflected and transmitted power, means the conversion of power into the higher order modes, this is interpreted as radiation into the continuous spectrum in the case of an open structure. Therefore, in the present approach the radiated power is given by the total power of the higher order modes of the partially filled parallel-plate waveguide. Because the structure under consideration is lossless, the total power must be conserved, and such a conservation condition is used as a gauge of our numerical accuracy.

Finally, numerical results are presented to quantify the two major effects of the transition waveguides: the radiation loss due to the curvature of the waveguides and the change in the coupling length of the structure as a whole. On the basis of these numerical results, useful guidelines are developed for the design of directional couplers composed of dielectric waveguide.

2. Method of Analysis

Fig. 1 shows the geometrical configuration of the dielectric waveguide directional coupler under investigation. It consists of one uniform coupling region which is connected to uniform input/output waveguides by curved transition sections. In the present study, we assume that the center line of the transition profile is characterized by a hyperbolic tangent function, as was previously done[3]-[5]. The structure is symmetric with respect to both the x and the y axis. In this paper, only this special geometry is considered for simplicity; other geometrics can be handled in similar fashion, although the computations will be more complicated. Utilizing the symmetry property, we may bisect the structure in both x and y directions and consider only a quarter of the structure with appropriate boundary conditions, as shown in Fig. 2. The stepped structure can be viewed as consisting of a series of uniform, partially filled parallel-plate waveguides connected by junctions. A basic equivalent network has been developed for a junction between two uniform dielectric waveguides[3]. The basic equivalent network for all the junctions can be put in cascade through transmission line sections to form an overall network for the entire stepped dielectric structure. The scattering of the guided mode

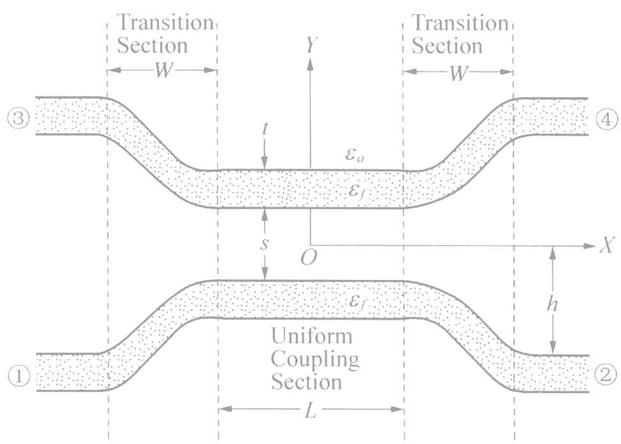

Fig. 1 Structure configuration of parallel dielectric wavcguide directional coupler

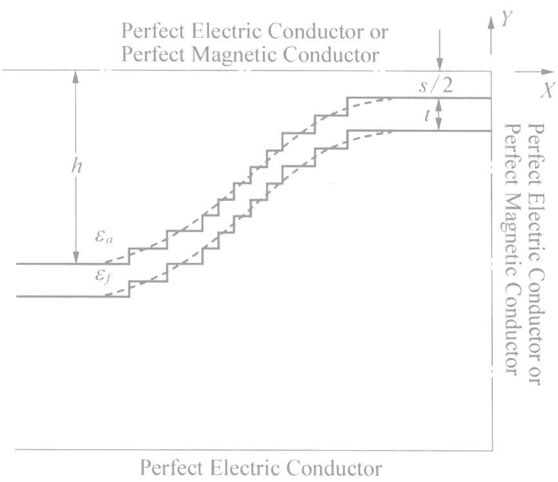

Fig. 2 Bisected structure with boundary conditions

by the staircase structure can be analyzed in terms of the reflection characteristics by each basic unit.

Fig. 3 depicts the ith basic unit that consists of the ith step discontinuity between two uniform waveguides at the point $x = x_i$ and the uniform waveguide of length l_i between the points x_i and x_{i-1}. The analysis procedure of the reflection characteristic for the basic unit is outlined below.

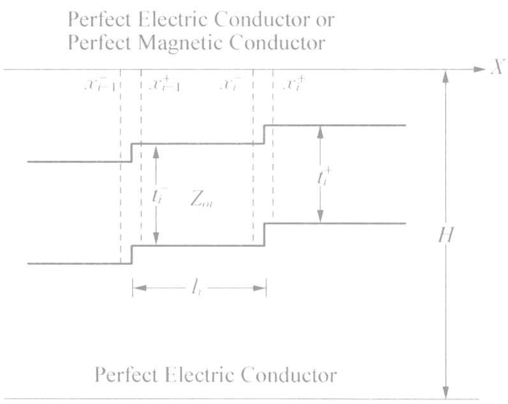

Fig. 3 The ith basic unit of the stepped structure

Since the terminal plane of the stepped structure at $x=0$ is known to be either a perfect electric wall or a perfect magnetic wall, the input impedance matrix $Z(x_i^+)$ at the $x = x_i^+$ plane looking to the right can be determined by the impedance transform technique. Therefore, $Z(x_i^+)$ is considered as a known matrix for the ith basic unit. It is well known[6] that the electromagnetic fields in each uniform waveguide section can be represented by a complete set of mode functions; for a TE polarized mode in the region with the dielectric layer of thickness t_i^+, we have the tangential field components represented by

$$E_z^{(i)}(x, y) = \sum_n V_n(t_i^+, x)\phi_n(t_i^+, y) \quad (1)$$

$$H_y^{(i)}(x, y) = \sum_n I_n(t_i^+, x)\phi_n(t_i^+, y) \quad (2)$$

where $\phi_n(t_i^+, y)$ is the nth mode function and $V_n(t_i^+, x)$ and $I_n(t_i^+, x)$ are the voltage and the current of the nth mode. It is noted that throughout this paper, the summation over n extends from 1 to ∞. By matching the tangential field components at the ith discontinuity, the waveguide problem is reduced to the analysis of an equivalent network for the modal voltages and currents which are on the two sides of the ith step and are related by

$$V_m(t_i^-, x_i^-) = \sum_n (Q_i)_{mn} V_n(t_i^+, x_i^+) \quad (3)$$

$$I_m(t_i^-, x_i^-) = \sum_n (Q_i)_{mn} I_n(t_i^+, x_i^+) \quad (4)$$

where $(Q_i)_{mn}$ is the coefficient of coupling between the mth mode on the left and the nth mode on the right of the ith step discontinuity and is defined by the scalar product

$$(Q_i)_{mn} = \langle \phi_m(t_i^-, y) | \phi_n(t_i^+, y) \rangle = \int_0^H \phi_m(t_i^-, y)\phi_n(t_i^+, y)\,dy \quad (5)$$

where ϕ_m and ϕ_n are, respectively, the mode functions in the uniform dielectric waveguides. They are the solutions of the Sturm - Liouville eigenvalue problem[6].

Equations (3) and (4) may be written in matrix form as

$$V(x_i^-) = Q_i V(x_i^+) \quad (6)$$

$$I(x_i^-) = Q_i I(x_i^+) \quad (7)$$

where $V(x_i^-)$ and $I(x_i^-)$ are column vectors with the transmission line voltage and current of the TE mode on the left of the ith step, and $V(x_i^+)$ and $I(x_i^+)$ are column voltage and current vectors of the TE mode on the right of the ith step. Since the voltage and current are related as

$$V(x_i^-) = Z(x_i^-)I(x_i^-) \quad (8)$$

$$V(x_i^+) = Z(x_i^+)I(x_i^+) \quad (9)$$

(6) and (7) may be expressed by

$$Z(x_i^-) = Q_i Z(x_i^+) Q_i^{-1} \quad (10)$$

We assume that the dielectric materials forming the waveguide in Fig. 1 are lossless. The Sturm - Liouville eigenvalue problem of the multilayer planar dielectric structure is Hermitian, because of the perfectly electric or magnetic conducting bounding plates at $y = 0$ and $-H$. Therefore, all eigenvalues are real and all eigenmode functions can be chosen to be real, and we have $Q_i^{-1} = Q_{it}$. Then (10) can be written as

$$Z(x_i^-) = Q_i Z(x_i^+) Q_{it} \quad (11)$$

where t stands for the transpose, and Q_i is the coupling coefficient matrix of the ith step whose elements are determined by (5).

From (11), the reflection coefficient matrix $\Gamma(x_i^-)$, at the $x = x_i^-$ plane looking to the right. can easily be obtained as

$$\Gamma(x_i^-) = [Z(x_i^-) + Z_{0i}]^{-1}[Z(x_i^-) - Z_{0i}]. \tag{12}$$

Then, the input impedance matrix at the $x = x_{i-1}^-$ plane looking to the right is determined by the impedance transform technique as

$$Z(x_{i-1}^+) = Z_{0i}[I + H_i\Gamma(x_i^-)H_i][I - H_i\Gamma(x_i^-)H_i]^{-1} \tag{13}$$

where Z_{0i}, and H_i are, respectively, the characteristic impedance and the phase matrices of the ith step discontinuity. They are all diagonal matrices, and their elements are

$$(Z_{0i})_{mn} = \delta_{mn}K_{xin}/\omega\epsilon_0\epsilon_{ein} \tag{14}$$

$$(H_i)_{mn} = \delta_{mn}\exp(-jK_{xin}l_i) \tag{15}$$

where δ_{mn} stands for the Kronecker delta, K_{xin} is the propagation wavenumber in the x direction for the n th mode in the dielectric waveguide of the ith section, and ϵ_{ein} is the effective dielectric constant of the nth mode. Thus, the reflection coefficient matrix of any step junction can be determined by using (5) and (11)-(15).

With the bisections in both the x and the y direction, there are four different combinations of boundary conditions. For an incident guided mode from waveguide 1, we analyze the four separate substructures, as depicted by Fig. 2, with appropriate boundary conditions. In each case, the energy is totally reflected, and the reflection coefficient matrices, accounting for the coupling to higher order modes, are denoted by R_{ss}, R_{sa}, R_{as} and R_{aa} for the four cases. The subscripts s and a stand for the symmetric and antisymmetric bisections, respectively; the first subscript represents the symmetry property with respect to the x axis and the second with respect to the y axis. The scattering coefficient matrices of the overall structure are found to be given by

$$G_1 = (R_{ss} + R_{sa} + R_{as} + R_{aa})/4.0 \tag{16}$$

$$T_2 = (R_{ss} - R_{sa} + R_{as} - R_{aa})/4.0 \tag{17}$$

$$T_3 = (R_{ss} + R_{sa} - R_{as} - R_{aa})/4.0 \tag{18}$$

$$T_4 = (R_{ss} - R_{sa} - R_{as} + R_{aa})/4.0 \tag{19}$$

Here G_1 is the reflection coefficient matrix of waveguide 1, and T_2, T_3, and T_4 are the transmission coefficient matrices from waveguide 1 to waveguides 2, 3, and 4, respectively. The scattering of an incident guided mode is then simply determined for the coupling structure by (16)-(19).

3. Numerical Results

Referring to Fig. 1, we assume that each individual waveguide supports only the fundamental guided mode. A fundamental guided mode of unit power is incident from the left into waveguide 1. We are interested in the effect of the transition sections on the reflection of the fundamental mode in waveguide 1 and the transmission of the same mode into all other waveguides. While the individual waveguides support only a single mode, the coupled waveguide system is designed to support two surface wave modes, one symmetric and the other antisymmetric. The two modes propagate with different phase velocities; consequently, they interfere with each other constructively or destructively. This results in the transfer of energy back and forth between the two coupled waveguides.

Fig. 4 shows the effect of the transition length on the scattered powers of the fundamental mode in each waveguide and the total radiated power from the entire nonuniform dielectric structure, which represents the

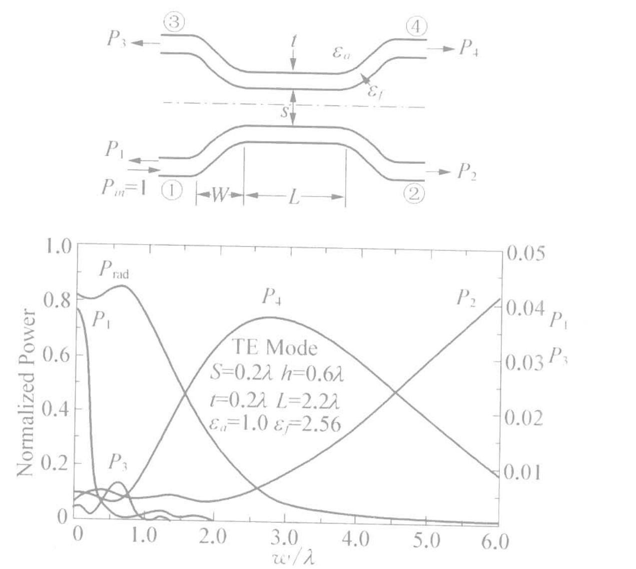

Fig. 4 Dependence of scattered powers on transition length

coupling to the higher order modes. The length of the uniform coupling region is fixed at $L = 2.2\lambda$, where λ is the free-space wavelength. It is noted that the scale for the reflected power P_1, and reverse-coupled power P_3, is exaggerated, as shown on the right-hand side of the figure. They are quite small and can be neglected as long as the transitions are not too short. For a fixed length of the coupling region L, the transition regions have two major effects: one is the radiation loss and the other is the change in the effective coupling length. For the case analyzed, the radiation loss exceeds 80 percent of the incident power for a transition length of less than one wavelength. When the transition length is increased, the radiation loss decreases rapidly and the division of the transmitted power between waveguides 2 and 4 varies continually. For the length of the uniform coupling region, $L = 2.2\lambda$, it is expected that a very long transition length will be required to realize a coupling close to 100 percent to either waveguide 2 or 4. For a reasonable transition length, it is expected that we may adjust the length of the uniform coupling region to achieve any desired ratio of the powers between waveguides 2 and 4, as discussed next.

Fig. 5 shows the transmission characteristics of the coupler, with the structure parameters depicted in the inset. The coupling length over which a complete power transfer takes place is determined by

$$L_{eff} = \lambda / 4.0 \mid n_e - n_o \mid \tag{20}$$

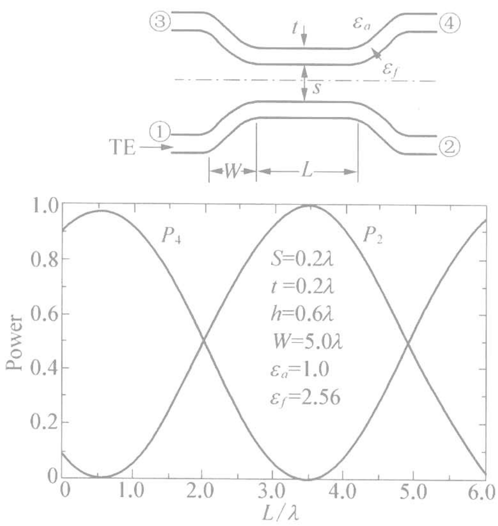

Fig. 5 Dependence of transmitted power on the length on the uniform coupling region

where n_e and n_o are effective indices of the first even and the first odd mode of the uniform dielectric waveguide, respectively. For a 3 dB coupling, the coupling length is one half of the value of L_{eff} given above. For the case shown, the coupling length is observed to be about 2.9λ, and the 3 dB coupling length is about 1.45λ. Evidently, 100 percent coupling is possible and any ratio of powers between waveguides 2 and 4 can be achieved.

From Figs. 4 and 6, we observe that the radiation loss is the main problem for the dielectric waveguide directional coupler with curved transition sections if the transition length is small. It is expected intuitively that when the transition length or the radius of curvature of the bend is sufficiently large, the radiation loss will become small. The question is how large a transition length is needed to make the radiation loss negligible or tolerable. This is what we intend to illustrate. Fig. 6 shows the effect of the transition length on the radiated power, P_{rad} for four values of the separation distance h. It is found that as long as the transition length $w > 5\lambda$, the radiated power can be kept below 2 percent of the incident power, and it becomes insensitive to the separation distance h and the transition length w. Fig. 6 also shows that, for small w, the larger the separation distance h, the stronger the radiation. This is because of the stronger fields near the discontinuities for larger h. These facts establish a quantitative basis for the design of dielectric waveguide directional couplers, as far as the undesirable radiation is concerned.

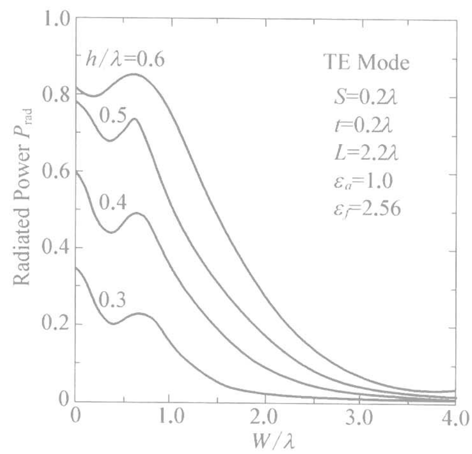

Fig. 6 Effect of the transition length on the radiated power for the parallel dielectric waveguide coupler

The curves in Fig. 7 show the effect of the transition length on the effective coupling length of a 3 dB coupler for several values of the separation distance h. As depicted in the inset, the effective coupling length includes the effect of the curved section, in addition to the uniform coupling region. In other words, we may define a correction length as the difference between the effective coupling length and the actual length of the uniform coupling region. Here, we observe that the longer the transition length w, the larger the correction length ($L_{eff} - L$). Furthermore, for the same transition length, the correction length becomes smaller when the separation of input/output waveguides increases. The reason for this is that the larger the separation, the steeper the curved sections and the weaker the coupling in the transition region. From the curves in Fig. 7, we found that the correction to the coupling length becomes quite significant when the transition length is large. Therefore, while increasing the transition length to reduce the scattering losses, it is important to keep in mind that the coupling length has to be adjusted accordingly.

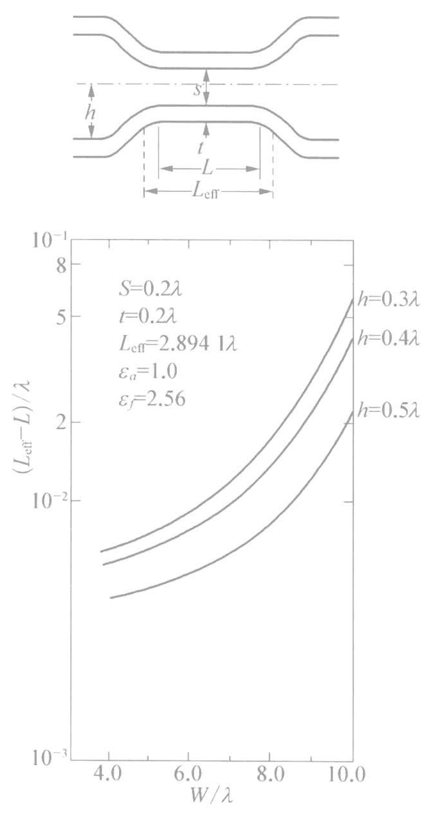

Fig. 7 Effect of the transition length on the coupling length for the parallel dielectric waveguide coupler

4. Conclusion

We have investigated the coupling of the guided modes on curved dielectric waveguide directional couplers by the staircase approximation method, which combines the building block approach of multimode network theory with a rigorous mode-matching procedure. Extensive numerical data have been obtained to quantify the propagation and scattering characteristics of the coupling structure. The power of the fundamental mode in each input/output waveguide is carefully examined for the parallel dielectric waveguide coupler. It is found that the reflection, reverse coupling, and radiation decrease rapidly as the transition length is increased; they are practically negligible for a transition length greater than five wavelengths. For a long transition region, it is shown that the coupling length has to be adjusted to account for the additional coupling of the transition regions. Based on these results, some useful guidelines for the design of the coupling structures are thereby suggested.

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