ELECTROMAGNETIC WAVE PROPAGATION IN ANISOTROPICALLY CONDUCTING TAPE HELIX SLOW WAVE STRUCTURES

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DOCTOR OF PHILOSOPHY

By

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DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled **"Electromagnetic Wave Propagation in Anisotropically Conducting Tape Helix Slow Wave Structures"** submitted at **Jaypee Institute of Information Technology, Noida, India,** is an authentic record of my work carried out under the supervision of **Prof. N. Kalyanasundaram**. I have not submitted this work elsewhere for any other degree or diploma.

(Signature of the Scholar)

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "**Electromagnetic Wave Propagation in Anisotropically Conducting Tape Helix Slow Wave Structures**", submitted by **G.Naveen Babu** at **Jaypee Institute of Information Technology, Noida**, **India** is a bonafide record of his original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

(Signature of Supervisor)

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SYNOPSIS

1.1 INTRODUCTION

High power, broad bandwidth, high gain, high efficiency, long life times, excellent reliability and robustness are among the most important features of Traveling Wave Tube Amplifiers (TWTA). The linear beam travelling wave tube amplifier holds a prominent place among the present day power amplifiers at microwave frequencies despite the fact that Integrated Circuit (IC) technology is advancing all the time. The amplification of the radio frequency (RF) signals in TWTA is achieved from the electron beam-wave interaction process. During this process of electron beam-wave interaction, transfer of the kinetic energy from the electron beam to the electromagnetic wave supported by the slow-wave structure takes place. The focus of research here is on helix-type slow wave structures for TWTA.

1.2 MODELS OF HELIX-TYPE SLOW-WAVE STRUCTURES

The helix is geometrically simple and easy to fabricate; however, the helix geometry makes the task of finding exact solutions of boundary value problems for Maxwell's equations quite difficult. For this reason, a number of simplified models for the helix have been proposed in the literature with a view to making the analysis of helical structures tractable. The prominent among such models are those of a tape helix and a sheath helix.

The actual helix ribbon used in TWTs has a finite thickness and finite width with rounded edges. Also, the helix is of finite length with finite conductivity. By letting the thickness of the helix ribbon (of rectangular cross section) go to zero and the conductivity of ribbon material go to infinity, we arrive at the tape-helix model. Thus, a tape helix consists of an infinitesimally thin and perfectly conducting tape (of constant width) wound into a helical structure (of constant pitch). In a practical TWT, the helix is supported by a number of dielectric support rods which could typically be of a rectangular, circular or specially-tapered cross section and the entire assembly is enclosed in a perfectly conducting metal envelope. Discrete dielectric support rods geometry of the SWS causes an inhomogeneous loading of the helix.

For practical helical SWS, the dielectric support rods are usually made of APBN (anisotropic pyrolytic boron nitride ϵ_r = 5.1), quartz (ϵ_r = 3.78), beryllia (ϵ_r = 6.65). For the purpose of analysis, the symmetrically placed dielectric support rods, which are modelled to be wedge shaped, are azimuthally smoothed out into a continuous dielectric tubular region between the helix and the outer conductor of an effective permittivity ϵ_{eff}. The effective permittivity may be computed by azimuthal averaging the nonhomogeneous permittivity function $\epsilon(r,\theta)$. The inhomogeneity caused by dielectric support structures other than the wedge-type may also be accounted for in a model by azimuthally smoothing out the supports into a finite number of contiguous dielectric tube regions, leading to stratified homogeneous layers.

The other type of model that is of interest to most researchers is an open tape helix model in which the dielectric support structure is not considered for the analysis and instead free space extending to infinity from the helix surface is considered. Based on the assumption about the current-flow along the surface of the tape, the modelling of tape helix may be classified as *anisotropically conducting* or *perfectly conducting*. In an anisotropically conducting model of the tape helix, the contribution of the tape current density component perpendicular to the winding direction is neglected. The error resulting out of this assumption of neglecting the perpendicular component of the surface current density is reasonably acceptable for narrow tape helix structures. In the case of perfectly conducting tape helix model, it is no longer insisted that the tape helix is perfectly conducting along the winding direction only.

In this work, we consider an anisotropically conducting model of a tape helix of infinite length, constant pitch and tape width, infinitesimal tape thickness and infinite tape-material conductivity surrounded by free space. The axis of the helix is taken along the z – coordinate of a cylindrical coordinate system (ρ,φ,z). The radius of the helix is a, the pitch is p, the width of the helix in the axial direction is w, and the pitch angle ψ is then given by $\tan\psi = p/2\pi a$.

When the spacing between the turns and the ribbon width of an anisotropically conducting tape helix are made to approach zero, the resultant structure becomes electrically smooth. At the boundary surface $\rho = a,$ the boundary conditions for the electric field may be approximated by the conditions that the conductivity in the direction along the tape winding direction is infinite, whereas the conductivity in the direction perpendicular to the winding direction on the tape surface is zero. The use of these boundary conditions permits a solution for the electromagnetic field guided by the helix to be obtained with relative ease. This anisotropically conducting cylinder model of a tape helix is called the sheath helix. Note that the sheath helix is a uniform structure unlike the tape helix, which is a periodic structure. A physical approximation to the sheath-helix model could be reasonably made by winding a flat tape of axial width p, consisting of a large number of fine wires all insulated from one another on a cylindrical form of radius a, with all windings being wound side by side (with no gap in between) on the form.

It is now well established that the tape-helix model gives a better approximation to the slow-wave structure of a TWT amplifier than the theoretical model of sheath-helix over the entire frequency range of operation. Moreover, there is no possibility of simulating the input and the output ports of the amplifier with the sheath-helix model. Thus, a field-theoretical analysis of the dispersion characteristics of the tape-helix slow-wave structure will be of immense interest to the TWT community.

1.3 ANALYSIS OF ANISOTROPICALLY CONDUCTING OPEN TAPE HELIX MODEL

An indepth study of electromagnetic wave propagation on helical conductors has been performed by Samuel Sensiper way back in 1952 [1]. He has outlined essentially two approaches for analysing the tape-helix problem. Using the first approach, he has demonstrated the feasibility of an exact solution for the tape helix; unfortunately, he chose to eschew this approach on the ground that “it is of no practical use for obtaining useful numerical results or for determining the detailed character of the solutions” preferring instead a second approach that involved an apriori assumption about the current distribution on the tape as a result of which it was possible to satisfy the boundary conditions on the tangential electric field only approximately. Nevertheless, it is this latter approach that has been endorsed by the majority of later generations of research workers in the TWT area mainly because of its tractability. All variants of this second simplified approach are characterized invariably by a common assumption, namely, that the tape current density component perpendicular to the winding direction may be neglected without much error. A notable exception to the practice of satisfying the tangential electric field boundary condition only along the centerline of the tape is the variational formulation developed by Chodorow and Chu [2] for cross-wound twin helices wherein the error in satisfying the tangential electric field boundary condition is minimized for an assumed tape-current distribution by making the average error equal to zero. The rationale behind the approach of Chodorow and Chu for single-wire helix has been outlined by Watkins in his book [3] assuming that (i) the tape current flows only along the winding direction, (ii) it does not vary in phase or amplitude over the width of the tape, and (iii) its phase variation is according to $\beta_0 z$ for z corresponding to a point moving along the center-line of the tape where $\beta_0 = \beta_0(\omega)$ is the guided- wave propagation phase constant at the radian frequency ω.

The method adopted for the solution of the cold-wave problem for the tape helix in this work derives from the following fact: If one is willing to neglect in any case the contribution of the perpendicularly directed current density component on the tape then there is neither a need for any apriori assumption regarding the tape-current distribution nor is there any difficulty in satisfying the tangential electric field boundary condition over the entire width of the tape. The hypothesis that the transverse component of the tape-current density is zero may be incorporated explicitly into the model by assuming that the tape helix is made out of an anisotropic material exhibiting infinite conductivity in the winding direction but zero conductivity in the orthogonal direction. This anisotropically conducting model for the tape helix leads to considerable simplification of the solution of the boundary value problem for the guided modes supported by an open helical structure. First of all, the boundary conditions give rise to only a single infinite set of linear homogeneous equations for determining the modal amplitudes of the tape-current density. Moreover, the approximate secular equation, for determining guided- mode propagation constant, resulting from setting the determinant of the coefficient matrix, corresponding to a symmetric truncation of the infinite set of equations, to zero will be in the form of a series whose terms decrease rapidly in magnitude with the order of truncation. This last feature of the truncated secular equation is quite attractive from a computational point of view since it then becomes possible to secure a fairly accurate estimate of the dispersion characteristic (β_0 Vs k_0, where $k_0 \triangleq \omega/c$ is the free-space wave number) with a reasonably low order of truncation. The entire analysis is of course based on the premise that the transverse component of the tape-current density does not have any significant effect on the value of the propagation constant even for tapes which are not narrow.

In this work, we shall see how the homogenous boundary value problem for the standard model of an open tape helix (that neglects the component of the tape-current density perpendicular to the winding direction) can be solved exactly without invoking any a priori assumption about the tape-current distribution. A key step in our approach is to recognize the periodicity of the tape-current density as a function of the skewed variable $\hat{\zeta} = z - \phi p/2\pi$ (p is the helix pitch) and make use of this periodicity to expand the tape-current density in a Fourier series in $\hat{\zeta}$. Similar expansions of the tangential electric field components restricted to the tape surface enable all the tape-helix boundary conditions to be satisfied exactly and the dispersion equation to be obtained. The dispersion equation takes the form of a determinantal condition on an infinite-order matrix. The approximate dispersion equation resulting from a symmetric truncation of the matrix can be solved numerically to obtain the dispersion characteristic.

1.3.1 NUMERICAL COMPUTATION

The approximate dispersion equation for a truncation order $N = 10$ and for the parameter values of $\hat{w} = 1/2$ and $\psi = 10°$ is solved numerically for $k_{0a}(\beta_{0a}), \beta_{0a} \geq 0$.The approximate tape-helix dispersion curve is seen to follow the dominant-mode sheath-helix dispersion curve quite closely in the middle portion of the first two allowed regions exhibiting, however, a marked downward shift everywhere from the sheath -helix dispersion curve in the third allowed region. It may also be observed from the dispersion curve that, the tape-helix dispersion curve tends to bend downward towards the forbidden-region boundaries in all the three allowed regions.

The solution for $k_{0a}(\beta_{0a})$ within the forbidden regions acquires a small imaginary part (on the order of 10^{-5}) on account of $\tau_{-1a}, \tau_{-2a}\ and\ \tau_{-3a}$ ($\tau_{na}^2 = \beta_{na}^2 - k_{0a}^2, n \in \mathbb{Z}$) becoming purely imaginary within the $1st$, the $2nd$ and the $3rd$ forbidden region respectively where the nth forbidden region for $n \in \mathbb{Z}$ is taken to be the portion of the $\beta_{0a} - k_{0a}$ plane inside the (inverted) triangle formed by the straight lines $k_{0a} = -\beta_{0a} + n \cot\psi$, $k_{0a} = \beta_{0a} - n \cot\psi$ and $k_{0a} = (1/2)\cot\psi$. It is thus seen that the mode constant τ_{-na} of the $-n^{th}$ space-harmonic contribution to the total field becomes imaginary in the n^{th} forbidden region, and that the resultant Poynting vector acquires a small radial component in order to account for the radiation of power from the $-n^{th}$ space harmonic.

It is observed that the normalised phase speed v_p of the sheath helix is constant at approximately 20% to that of the speed of the light. Observing the normalised phase speed of the open tape helix in the allowed regions, the phase speed is nearly equal to that of the sheath helix for $\beta_{0a} \in \{(2,4)\,,(7.5,9),\ (13.5,14.5)\}$, which may be used for the beam wave interaction and amplification. It is thus observed that the phase speed of the tape helix is nearly equal to 20% of the speed of light in the region of possible interaction with electron beam.

It may be observed from the magnitude and the phase plots of the surface current distribution that (i) the surface current density magnitude has a maximum along the center line of the tape irrespective of its width, and (ii)tends to acquire symmetrically located secondary maxima of equal magnitude on either side of the central maximum as the tape width increases. The phase of the current distribution on the other hand exhibits a nearly linear variation across the width of the tape the deviation from linearity increasing with the tape width.

1.4 ANALYSIS OF ANISOTROPICALLY CONDUCTING DIELECTRIC LOADED TAPE HELIX MODEL

The practically important case of a dielectric-loaded tape-helix enclosed in a coaxial perfectly conducting cylindrical shell is also analysed. For the purpose of analysis, the symmetrically placed dielectric support rods, which are modelled to be wedge shaped, are azimuthally smoothed out into a continuous dielectric tubular region between the helix and the outer conductor of an effective permittivity ϵ_{eff}. The effective permittivity may be computed by azimuthal averaging the nonhomogeneous permittivity function $\epsilon(r,\theta)$. The homogeneous boundary value problem is solved taking into account the exact boundary conditions. The boundary value problem is solved to yield the approximate dispersion equation which takes the form of the solvability condition for an infinite system of linear homogeneous algebraic equations viz., the determinant of the infinite-order coefficient matrix is zero. The dispersion characteristic is numerically computed. The tape-current distribution is estimated from the null-space vector of the truncated coefficient matrix corresponding to a specified root of the dispersion equation.

1.4.1 NUMERICAL COMPUTATION

From the numerical computation for a truncation order of $N = 20$, it is seen that the dispersion characteristic enters the first allowed region (slow wave region) of the anisotropically conducting model of open tape helix from the fast wave region. The dispersion curve first increases with increase in β_{0a} and then decreases. The characteristic reaches approximately zero at the meeting point of the forbidden region boundaries and increases as it enters the second allowed region of the open tape helix model. The peak value of the dispersion curve in the second 'allowed region' is slightly more than the peak value in the first 'allowed' region. The shape of the dispersion curve in the second 'allowed' region is then seen to repeat periodically in the subsequent 'allowed' regions also. It is observed that the dielectric loaded sheath helix curve is no longer an approximation to the dielectric loaded tape helix model.

In addition to the dominant mode of the dispersion characteristics, dielectric-loaded tape helix supports an infinite number of higher modes. The behaviour of the dispersion curves of modes higher than the third tends to be more and more chaotic with increasing values of β_{0a}. It is also observed from the plot of phase speed v_p vs β_{0a}, that the normalised phase speed v_p of the dielectric loaded sheath helix is approximately 13% of the speed of light. Observing the normalised phase speed of the dielectric loaded tape helix, the phase speed is more than 2 times that of the speed of light for very small values of β_{0a} ($\beta_{0a} < 0.3$). As soon as they enter the 'allowed region', the phase speed reduces to 50% of that of the speed of the light. Towards the end of the first 'allowed region' and thereafter, the speed varies from 1% and 20% of the speed of light. The only nearly constant phase speed region of the dielectric loaded tape helix useful for the purpose of interaction with electron beam and amplification is for $\beta_{0a} \in (1.5,3)$. It is to be noted that the phase speed of the dielectric loaded tape helix structure is 50% to that of the speed of light in the aforesaid region. For this reason, the relativistic effects (relativistic variation of electron mass with speed) have to be taken into while analysing the beam-wave interaction in a TWT amplifier configuration.

It is also observed from the plot between normalised phase speed and k_{0a} that the normalised phase speed is nearly constant for $k_{0a} \in (0.45, 1.28)$. For a helical radius $a = 0.56896$ [24], it is found that the dielectric loaded tape helix may be operated in the frequency range of 4.2 GHz to 10.9 GHz *i.e.*, C-band and part of X-band of microwave frequencies.

The observation drawn from the magnitude and the phase plots of the surface current distribution are: (i) the surface current density magnitude has minima along the centre line of the tape irrespective of its width, and (ii) tends to increase symmetrically along the sides of the tape towards the edges to reach maximum as the tape width increases. The phase of the current distribution on the other hand exhibits a nearly linear variation across the width of the tape. The deviation from linearity increases while moving away from centre of the tape with a phase discontinuity occurring nearer to the edges of the tape.

1.5 CONCLUSION

The main conclusion that may be drawn from the present study on anisotropically conducting open tape helixis the following: The dominant-mode dispersion characteristic of the sheath helix is an excellent approximation to that of an open tape helix in the first two allowed regions except close to the forbidden region-boundaries provided that the neglect of the transverse component of the tapecurrent density doesnot give rise to any appreciable error even for tapes which are not narrow. Whether such an hypothesis is true or false can be ascertained only through an analysis of guided electromagnetic wave propagation that fully accounts for the transverse component of the tape-current density. Based on the outcome of such a study (which is carried out in the [4]), it is proposed to extend the method adopted for the derivation of the tape-helix dispersion equation to a full field analysis of the practically important case of a dielectric-loaded helical slow-wave structure enclosed in a coaxial metal cylindrical shell and supported by azimuthally symmetrically placed dielectric rods. The effect of the dielectric support rods will have to be modeled by a homogeneous dielectric the effective dielectric constant of which can be determined in terms of the geometric arrangement of the support rods and the actual dielectric constant of the rod material.This process of homogenization is equivalent to replacing the azimuthally nonhomogeneous dielectric constant of the annular region between the helix and the outer conductor by its azimuthal average, which becomes a constant independent of the radial coordinate, for azimuthally symmetrically placed wedge-type support rods. In any case, it is necessary to smooth out any kind of azimuthal nonhomogenity before attempting a solution of the cold-wave problem because any axial asymmetry of the slow-wave structure would be inconsistent with the property of geometrical invariance under simultaneous translation and rotation exhibited by an infinite helical structure.

The main conclusion that may be drawn from the present study on anisotropically conducting dielectric loaded tape helix is the following: The dominant mode dispersion characteristic of the sheath helix is no longer an approximation of the dielectric loaded tape helix. There are infinite number of modes supported by a dielectric-loaded tape helix. The modes higher than the third exhibit a chaotic behaviour. Only the dominant mode dispersion curve is useful for the interaction and amplification purpose. Effective electron beam-wave interaction for amplification purpose is only possible in the constant phase speed region of the first ‘allowed region’. The magitude of the surface current density across the width of the tape is a minimum at the center of the tape and reaches a maximum along the edges of the tape. The phase variation of the current density is linear from the center of the tape to the edges of the tape with symmetric behaviour.

1.5 ORGANISATION OF THESIS

The thesis is organised in the following way. Chapter 1 introduces the importance of the microwave technologies and its usefulness in military and radar applications. Chapter 1 also compares the solid state devices and traveling wave tubes (TWTs). Brief introduction about the types of microwave tubes, construction and working principle of TWTs are provided. Research by the TWT community in early 1900s with the development of thin wire helical TWTs by Pocklington to the work carried out till date on tape helix TWTs are extensively reviewed in the literature survey section of Chapter 1.

Chapter 2 follows with the basic TWT structure and brief explanation about its important components that include electron gun, focussing magnets, helix slow wave structures and collector are provided in the initial sections of this chapter. As slow wave structures are the focus of research, their technicalities are dealt in detail. Also, the types of supporting dielectric structures with different configurations are briefly discussed.

Chapter 3 includes the modelling of helix-type TWT. The practically viable model of dielectric loaded anisotropically conducting tape helix with homogeneous loading arrangement is introduced. The effective permittivity of the homogeneously loaded dielectric support structure may be computed by azimuthal averaging the nonhomogeneous permittivity function. The other type of helical TWT model introduced is the anisotropically conducting model of open tape helix, that is, an arrangement without the dielectric support structure. Towards the end of the chapter, theoretical model of sheath helix structure is introduced.

Chapter 4 deals with the methods of solutions of Helmholtz equations. They are the method of Borgnis' potentials, the method of Hertz's vector potentials, and the method of longitudinal components. All three methods depend on the choice of the coordinate system in which the equations are to be solved. After a brief introduction about the orthogonal coordinate systems, the classification of guided waves in bounded cylindrical systems based on the value of transverse mode number into TEM modes, fast wave modes and slow wave modes are provided. Wave propagation in a periodic structures goverened by Floquet's theorem and space harmonics are covered in this chapter. The geometric invariance property of the helical structure for the field components in terms of space harmonics are represented in the end section of chapter 4.

Chapter 5 deals in detail the anisotropically conducting model of open tape helix. Chapter 5 introduces the open tape helix geometry. The guided wave field solutions of scalar Helmholtz equation in terms of Borgnis' potential are presented. Conditions for the existence of pure guided-wave modes are established in section 5.3 of chapter 5. In the following section, exact boundary conditions are tackled to derive the dispersion equation. The dispersion equation for free electromagnetic waves guided by an anisotropically conducting open tape helix is derived from the exact solution of a homogenous boundary value problem for Maxwell's equations without invoking any apriori assumption about the tape-current distribution. The derived dispersion equation is numerically analysed in the section 5.6 of chapter 5.

A numerical solution of the dispersion equation for a set of typical parameter values reveals that the tape-helix dispersion curve is virtually indistinguishable from the corresponding dominant-mode sheath helix dispersion curve except within the tape- helix forbidden regions. The surface current distribution of the open tape helix for a typical value of (β_{0a}, k_{0a}) obtained from the dispersion characteristic is computed and analysed towards the end of chapter 5.

The practically important case of a dielectric-loaded tape-helix enclosed in a coaxial perfectly conducting cylindrical shell is analysed in chapter 6. The homogeneous boundary value problem is solved taking into account the exact boundary conditions similar to the previous case of anisotropically conducting open tape helix model. The boundary value problem is solved to yield the approximate dispersion equation which takes the form of the solvability condition for an infinite system of linear homogeneous algebraic equations viz., the determinant of the infinite-order coefficient matrix is zero. For the numerical computation of the dispersion characteristic, all the entries of the symmetrically truncated version of the coefficient matrix are estimated by summing an adequate number of the rapidly converging series for them. The tape-current distribution is estimated from the null-space vector of the truncated coefficient matrix corresponding to a specified root of the dispersion equation.

Chapter 7 discusses the conclusions arrived at field analysis of the electromagnetic wave propagation in open and dielectric loaded tape helix structures. Future directions of research in this area are also provided in this chapter.

Appendix A describes the dielectric loaded model of sheath helix. The dominant-mode expressions are substituted in the boundary condition to derive the dispersion equation. The derived dispersion equation is numerically computed and results are plotted for comparison with dielectric loaded tape helix model.

1.6 FUTURE SCOPE OF RESEARCH

Work reported in the thesis may be extended in various possible directions. In chapter 6, the slow-wave structure modelled as a tape helix which is held in place inside a coaxial perfectly conducting cylindrical shell by symmetrically located dielectric support rods. With a view to making the problem of guided electromagnetic wave propagation through such a model of slow-wave structure tractable, the azimuthally periodic dielectric constant of the tubular region between the tape helix and the outer conductor has been replaced by its azimuthally averaged constant value of ϵ_{eff}. When the cross-sectional shape of the symmetrically placed dielectric support rods is anything other than a wedge $\{(r,\theta): a \leq r \leq b, \theta_1 \leq \theta \leq \theta_2\}$, the azimuthally averaged dielectric constant $\epsilon_{eff}(r)$ will turn out to be a function of the radial coordinate r. In this case, the region between the tape helix and the outer conductor is partitioned into finite number of tubular regions and each tubular region is characterized by the radially-averaged value of $\epsilon_{eff}(r)$ over its radial thickness. This is equivalent to approximating $\epsilon_{eff}(r)$ by a piecewise constant function in the radial variable r. The solution for the field components over the entire region between the tape helix and the outer conductor could then be obtained by enforcing the continuity of tangential field components across the interfaces separating two adjacent tubular regions with different values for the effective dielectric constant. This procedure has been adopted by Jain et al [5] to analyse guided wave propagation through a tape helix supported by dielectric rods of circular cross section based of course on an ad hoc assumption about the tape-current distribution.

It would also be of immense research interest to explore the possibility of directly solving the boundary value problem at least for a tape helix supported by symmetrically located wedge-type dielectric rods without first homogenizing the problem by azimuthal averaging. The choice of wedge shape for the support rods allows for a simple characterisation of the interfaces separating the dielectric and the vacuum regions using polar coordinates. Even this simplified problem of wedge-shaped dielectric support rods appears to be open till date.

The work reported in this thesis has made use of the anisotropically conducting model of the tape helix wherein the helix has been modelled to be of infinitesimal thickness and exhibiting infinite conductivity along the winding direction but zero conductivity in the orthogonal direction. The replacement of the anisotropically conducting model perfectly conducting model for an open tape helix gives rise to an ill-posed boundary value problem which has to be tackled using regularization techniques [6]. The work on the extension of the method used in [7] to analyse guided electromagnetic wave propagation through the dielectric-loaded perfectly conducting model of a tape helix is in progress and will be reported in due course. It is also worth exploring how the perfectly conducting model of the open tape helix should be modified so as to avoid having to grapple with an ill-posed boundary value problem altogether. One viable alternative would be model the tape helix to be of finite tape-material conductivity and finite tape thickness. Analysis of guided electromagnetic wave propagation through such a finitely conducting model of a tape helix and its extension to the corresponding dielectric-loaded finitely conducting model will be possible directions of future work in this fascinating area of microwave engineering.

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