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Simplified Tape-Helix Analysis of the Planar Helix Slow Wave Structure with Straight-Edge Connections

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Abstract— Tape-helix analysis for determining the dispersion characteristics as well as the interaction impedance of a planar helix slow-wave structure with straight-edge connections is presented. The analysis is simplified by using the characteristic equation for an infinitely wide planar helix in free space and incorporating the effect of transverse confinement by straight edge connections by applying the effective dielectric constant method. It is shown that the results calculated from analytical expressions derived in this manner match well the simulation results obtained from CST in the frequency range far from cut-off. The effective dielectric constant method is known to be inaccurate over the frequency range below cut-off. The simplified analysis is also used to determine the dispersion characteristics of a rectangular helix. The results based on the simplified analysis are shown to be more accurate than those from a previously reported complex tape-helix analysis of the rectangular helix.

Index Terms— Dispersion characteristics, effective dielectric constant (EDC) method, planar helix, tape-helix, TWT

I. INTRODUCTION

Traveling wave tubes (TWTs) are important due to their use in a wide range of applications such as high data-rate communications, airborne radar systems, concealed weapon or threat detection, materials processing, biomedical diagnostics, and chemical spectroscopy, etc. [1]–[2]. A slow-wave structure (SWS) is an important component of TWTs since it has a strong impact on their design and performance. Interaction impedance and phase velocity are two important characteristics of a SWS. Interaction impedance is a measure of the strength of interaction between electron beam and EM wave whereas the phase velocity is a parameter which determines the required beam voltage for velocity synchronization.

Circular helix SWS holds a unique position among various SWSs for TWTs due to its ability to offer strong beam-wave interaction over a wide bandwidth. For analyses based on field-theory, sheath-helix and tape-helix are the two approximations that have been used for studying the electromagnetic properties of circular helix SWS [3]–[4]. Sheath-helix analysis approximates the periodic helical structure as a homogeneous sheath, neglecting the effect of tape width and non-fundamental space harmonics. The tape-helix approximation gives a more accurate estimate of propagation characteristics but it requires a more complex

Fig. 1. Perspective view of planar helix slow-wave structure with straight-edge connections to realize a rectangular helix.

analysis. The tape-helix model considers the helix as a perfectly conducting tape with finite width and infinitesimal thickness. The tape width is considered to be much smaller than the pitch and the Fouquet's theorem is used to account for the effect of space harmonics.

Although very popular, the circular helix SWS is not easily amenable to printed circuit or microfabrication techniques and hence is difficult to fabricate at operating frequencies greater than 100 GHz. In this context, planar helix SWS has been proposed with a very good potential for fabrication using printed circuit or microfabrication techniques. The planar helix consists of a pair of parallel conducting screens which are infinite in transverse direction and conduct in different but symmetric directions. Slow-wave properties of the transversely infinite planar helix have been studied using sheath-helix as well as tape-helix approximation [5]–[7].

Rectangular helix, a practical version of planar helix, is realized by connecting the conductors in the top and bottom screens by inclined-edge connections. The rectangular helix has been investigated and its dispersion characteristics have been obtained using the sheath-helix approximation and average boundary conditions on four sides [8]. The rectangular helix has also been studied using the tape-helix approximation [9]. But realization of inclined-edge connections in the rectangular helix using printed circuit or microfabrication techniques is troublesome.

Planar helix slow wave structure with straight-edge connections (PH-SEC) is an easily realizable version of rectangular helix. As shown in Fig. 1, PH-SEC replaces the inclined-edge connections between the top and bottom conductors by straight-edge connections. Fabrication of the PH-SEC has been demonstrated using both printed-circuit [10] and microfabrication techniques [11].

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Dispersion characteristics of the PH-SEC have been studied in [12]-[13] using the sheath-helix approximation and the effective dielectric constant (EDC) method. But the analysis of PH-SEC based on tape-helix approximation, which would allow to take into account the effects of periodicity, has not been reported so far.

An initial approach for the tape-helix analysis of infinitely wide planar helix was reported in [5]. This analysis considered different space harmonic distribution in the y and z -directions, leading to a complex derivation with double infinite summation for field expressions. More recently, the tape-helix analysis of the rectangular helix has been reported in [9]. This approach makes use of the modified Marcanti's method and average power flow matching at boundaries. This tape-helix analysis considers the confinement of rectangular helix in both x and y directions in a single step, which leads to a complex analysis and rather complicated characteristic equation.

In this paper, we present a simplified analysis of PH-SEC using the tape-helix approximation. Initial results from such an analysis of PH-SEC have been reported briefly in [15]. Here, we report detailed steps of the analysis and detailed comparison of the analytical and simulation results. Compared to [5], we reduce the complexity in derivation by assuming that the fields have the same space harmonic distribution in both y and z -directions. The complexity is further reduced by obtaining the characteristic equation by simply equating the electric field parallel to the strips to zero, whereas [5] uses the rather complicated variational technique for deriving the characteristic equation. Compared to [9], the analysis is simplified by using the EDC method. The EDC method was developed to facilitate the analysis of 3-D rectangular waveguide [14]. It considerably eases the analysis by replacing the original 3-D waveguide by two related 2-D guides which can be analyzed simply. The results of EDC method are accurate in the frequency range far from cut-off.

In this paper, initially we derive the characteristic equation of an infinitely wide planar helix in free space using the tape-helix approximation. The effect of transverse confinement by straight edge connections is then incorporated by applying the EDC method. The characteristic equation so obtained is solved numerically to obtain the dispersion characteristics and interaction impedance.

Although the analysis presented here considers the PH-SEC to be situated in free space and ignores the effects of the supporting dielectric material and metal shielding, it does provide a simple and fast means to investigate the effects of tape width and space harmonics in the phase velocity and interaction impedance of PH-SEC. These results can be used for the initial selection of dimensions of the PH-SEC for a TWT with given target specifications. Moreover, the analytical method provides mathematical expressions for the field distribution for various modes of the structure and can thus help to find ways to avoid mode competition etc.

Section II presents the field expressions and the derivation of the characteristic equation of an infinitely wide planar helix in free space using the tape-helix approximation. This section also describes the application of EDC method to obtain the dispersion characteristics of PH-SEC. Section III compares the results obtained from tape-helix analysis with simulation results obtained from CST [16]. The results include

Fig. 2. Plan view (a), and cross-sectional view (b) of infinitely wide planar helix

normalized phase velocity and interaction impedance for the transverse antisymmetric mode of PH-SEC. This section also presents a comparison between the dispersion characteristics of the rectangular tape-helix obtained from the present simplified analysis and those obtained from the tape-helix analysis reported in [9]. The paper ends with a summary of important conclusions in Section IV.

II. TAPE-HELIX ANALYSIS

A. Analysis of planar helix

We first consider the infinitely wide structure corresponding to the PH-SEC shown in Fig. 1. As shown in Fig. 2, the infinitely wide planar helix can be modelled as a pair of arrays of parallel, straight and perfectly conducting strips. The strips in the top and bottom array are oriented at an angle $+\psi$ and $-\psi$ with respect to the y -axis, respectively. The top and bottom arrays are separated by a distance $2a$ in the x -direction (see Fig. 1 and Fig. 2(b)) and are infinitely wide in the y -direction. The thickness of the strips is assumed to be infinitesimally small. The periodic spacing between the strips are p_y and p_z and strip widths are w_y and w_z along the y - and z -directions, respectively. Wave propagation is assumed in the z -direction. The strip widths w_y and w_z are related to the actual width w of the strips as

$$w_y = w / \sin \psi \quad (1)$$

$$w_z = w / \cos \psi. \quad (2)$$

The planar helix remains unchanged under any one or any combination of the following four transformations:

$$(x, y, z) \rightarrow (-x, -y, z) \quad (3)$$

$$(x, y, z) \rightarrow \left(x, y \pm \frac{p_y}{2}, z \pm \frac{p_z}{2}\right) \quad (4)$$

$$(x, y, z) \rightarrow (x, y, z \pm p_z) \quad (5)$$

$$(x, y, z) \rightarrow (x, y \pm p_y, z). \quad (6)$$

When one considers these symmetry properties of the planar helix together with the Maxwell's equations, it can be concluded that the structure supports two independent solutions: transverse-symmetric and transverse-antisymmetric [17]. Since the operation of TWTs requires a non-zero value of the longitudinal electric field at the axis, we are interested in the transverse-antisymmetric solution here since this solution corresponds to longitudinal symmetric fields.

1) Field expressions

The Fouquet's theorem and Helmholtz's equation are used to write the general expressions for longitudinal fields in the planar helix. Region-1 and region-2 denote the regions outside and between the arrays, respectively. The expressions for the longitudinal electric and magnetic fields for the transverse-antisymmetric (longitudinal symmetric) mode in the two regions are:

$$E_{z1} = \sum_{n=-\infty}^{\infty} A_n \exp\{-u_n(x-a)\} \exp\left\{j \frac{2\pi n y}{p_y}\right\} \exp\{-j\beta_n z\} \quad (7)$$

$$E_{z2} = \sum_{n=-\infty}^{\infty} B_n \cosh(u_n x) \exp\left\{j \frac{2\pi n y}{p_y}\right\} \exp\{-j\beta_n z\} \quad (8)$$

$$H_{z1} = \sum_{n=-\infty}^{\infty} C_n \exp\{-u_n(x-a)\} \exp\left\{j \frac{2\pi n y}{p_y}\right\} \exp\{-j\beta_n z\} \quad (9)$$

$$H_{z2} = \sum_{n=-\infty}^{\infty} D_n \cosh(u_n x) \exp\left\{j \frac{2\pi n y}{p_y}\right\} \exp\{-j\beta_n z\}. \quad (10)$$

In (7)-(10), A_n , B_n , C_n , and D_n are the unknown amplitude constants for the n^{th} space harmonic; β_n is the propagation constant of the n^{th} space harmonic, which is related to the propagation constant of the fundamental space harmonic β_0 as $\beta_n = \beta_0 + (2\pi n/p_z)$, and u_n is the decay constant in the x -direction, obtained by the following equation:

$$u_n^2 = \left(\frac{2\pi n}{p_y}\right)^2 + \beta_n^2 - k_0^2 \quad (11)$$

where $k_0 = \omega(\mu_0 \epsilon_0)^{1/2}$ is the wave number in vacuum at the angular frequency ω .

2) Boundary conditions

Due to symmetry, we need only consider the structure for $x \geq 0$. Continuity of tangential electric field and discontinuity of tangential magnetic field at $x=a$ lead to the following boundary conditions:

$$E_{z1,n}(x=a) = E_{z2,n}(x=a) \quad (12)$$

$$E_{y1,n}(x=a) = E_{y2,n}(x=a) \quad (13)$$

$$[H_{z2,n}(x=a) - H_{z1,n}(x=a)] = J_{y,n} \quad (14)$$

$$[H_{y1,n}(x=a) - H_{y2,n}(x=a)] = J_{z,n} \quad (15)$$

where $J_{y,n}$ and $J_{z,n}$ are the surface current densities corresponding to the n^{th} space harmonic on the $x=a$ interface in the y - and z -directions, respectively. Assuming that the strip width is much smaller than the pitch, the current in the strips can be considered to be flowing only along the strips. Then we can express $J_{y,n}$ and $J_{z,n}$ in terms of $J_{\parallel n}$, the current flowing parallel to the strips corresponding to the n^{th} space harmonic:

$$J_{z,n} = J_{\parallel n} \sin \psi \quad (16)$$

$$J_{y,n} = J_{\parallel n} \cos \psi. \quad (17)$$

Similar to the tape-helix analysis of the circular helix in [4], the $J_{\parallel n}$ can be obtained by finding the Fourier components of the total current on the strips. The total current is assumed to have a constant magnitude J along the strip width and flowing parallel to the strips. The current is also assumed to have a phase variation according to $e^{-j\beta_0 z}$. The expression for $J_{\parallel n}$ is:

$$J_{\parallel n} = \frac{J w_z}{p_z} \text{sinc}\left(\frac{\beta_n w_z}{2}\right). \quad (18)$$

3) Characteristic equation

The expressions for the constants A_n , B_n , C_n , and D_n obtained by using the boundary conditions (12)-(15) are given as:

$$A_n = \frac{-J_n k_c^2 (j\omega\mu_0) \cosh(u_n a)}{u_n k_0^2 e^{u_n a}} \left[\sin \psi + \frac{1}{k_c^2} \frac{2\pi n}{p_y} \beta_n \cos \psi \right] \quad (19)$$

$$B_n = \frac{A_n}{\cosh(u_n a)} \quad (20)$$

$$C_n = \frac{-J_n \cos \psi \cosh(u_n a)}{e^{u_n a}} \quad (21)$$

$$D_n = \frac{-C_n}{\sinh(u_n a)} \quad (22)$$

where $k_c^2 = k_0^2 - \beta_n^2$.

The characteristic equation for determining β_0 is obtained by using the condition $E_{1\parallel}(x=a) = 0$ at the center of the strips [4]. $E_{1\parallel}$ is the component of the electric field intensity parallel to the strips and is given as:

$$E_{1\parallel} = \sum_{n=-\infty}^{+\infty} E_{1\parallel n} = \sum_{n=-\infty}^{+\infty} (E_{y1,n} \cos \psi + E_{z1,n} \sin \psi). \quad (23)$$

Fig. 3. Comparison of simulated and analytical results for a PH-SEC for three different pitch angles ($\psi=2.5^\circ, 5^\circ, 7.5^\circ$) with $a/b=0.25$, $a=0.48$ mm, and $w/p_z=0.2$. (a) Normalized phase velocity, (b) Interaction impedance.

Fig. 4. Comparison of simulated and analytical results for a PH-SEC for three different pitch angles ($\psi=2.5^\circ, 5^\circ, 7.5^\circ$) with $a/b=1$, $a=1.2$ mm, and $w/p_z=0.2$. (a) Normalized phase velocity, (b) Interaction impedance.

The following is the resulting characteristic equation for the infinitely wide planar helix:

$$\sum_{n=-\infty}^{+\infty} \left\{ \frac{\left(j\omega\mu_0 \right) u_n \cos^2 \psi \left(\frac{Jw_z}{p_z} \operatorname{sinc} \left(\frac{\beta_n w_z}{2} \right) \right)}{k_c^2 e^{u_n a}} \right\} \left[\sinh(u_n a) - \frac{\cosh(u_n a)}{u_n^2 k_o^2} \left(\frac{2\pi n}{p_y} \beta_n + k_c^2 \tan \psi \right) \right]^2 = 0. \quad (24)$$

Although (24) involves the sum of an infinite number of space harmonics, it converges with an error less than 0.5% when the first seven space harmonics are considered.

B. Effective dielectric constant (EDC) method

Next, we include the effect of transverse confinement of the planar helix by straight-edge connections by using the EDC method. As shown in Figs. 1-2, PH-SEC with dimensions $2a$ and $2b$ along the x - and the y -direction is considered. The 3-D PH-SEC is decomposed into two 2-D structures for simplifying the analysis [12]. The first 2-D structure is the infinitely wide planar helix of the previous sub-section and it takes into account the x -dependent profile of the PH-SEC. This structure captures the ‘slowing-down’ effect of the planar helix and yields a propagation constant denoted as β_1 .

The second 2-D structure takes into account the y -dependent profile, i.e., the transverse confinement of the PH-SEC. This structure is considered to be a dielectric slab of thickness $2b$ in the y -direction, infinite in the x -direction, and situated in free space. The dielectric constant of the slab is

taken to be $\epsilon'_{r,\text{eff}}$ which is calculated from the propagation constant β_1 obtained for the first structure:

$$\epsilon'_{r,\text{eff}} = \left(\frac{\beta_1}{k_o} \right)^2. \quad (25)$$

The second structure yields a propagation constant denoted as β_2 . The overall propagation constant is obtained by taking the weighted average of propagation constants β_1 and β_2 by using:

$$\beta = \frac{b\beta_1 + a\beta_2}{a+b}. \quad (26)$$

1) x -dependent profile

This step makes use of (24) for obtaining propagation constant β_1 . The pitch angle ψ in (24) needs to be modified to correctly capture the slowing down effect of the original PH-SEC [12]. The modified pitch angle ψ_{eff} is obtained as:

$$\psi_{\text{eff}} = \tan^{-1} \left(\frac{\text{pitch}}{4a + 4b} \right). \quad (27)$$

2) y -dependent profile

The infinite dielectric slab in the second step can support TM and TE modes which can be even or odd with respect to y . An even variation of E_x with respect to y is considered here to support the transverse anti-symmetric mode of the original SWS [12]. Thus the characteristic equation for the TE-even mode of the dielectric waveguide is used here. Relations to determine the propagation constant β_2 are:

Fig. 5. Comparison of simulated and analytical results for a PH-SEC for three different pitch angles ($\psi=2.5^\circ$, 5° , 7.5°) with $a/b=4$, $a=0.15$ mm, and $w/p_z=0.2$. (a) Normalized phase velocity, (b) Interaction impedance.

$$\frac{v_1}{v_2} = \tan(v_2 b) \quad (28)$$

$$\beta^2 = v_1^2 + k_1^2 = k_{\text{eff}}'^2 - v_2^2 \quad (29)$$

where $k_1^2 = \omega^2 \mu_0 \epsilon_0$ and $k_{\text{eff}}'^2 = \omega^2 \mu_0 \epsilon_0 \epsilon_{r,\text{eff}}'$ are the wave numbers in the free space and dielectric regions, respectively. The final propagation constant β is obtained by substituting β_1 and β_2 in (26).

C. Interaction impedance

The on-axis interaction impedance for the fundamental space harmonic is defined as

$$K_0 = \frac{E_{z,0}^2(0)}{2P\beta_0^2} \quad (30)$$

where $E_{z,0}(0)$ is the z -component of the electric field at $x=0$ for the fundamental space harmonic and P is the total power propagating through the SWS in the z -direction. The total power is the sum of the powers contributed by all the space harmonics. Since the powers of the higher order harmonics are negligibly small, the total power is calculated by adding up the power contributed by the first seven space harmonics only.

Fig. 6. Comparison of simulated and analytical results for a PH-SEC for three different pitch angles ($\psi=2.5^\circ$, 5° , 7.5°) with $a/b=1$, $a=0.15$ mm, and $w/p_z=0.2$. (a) Normalized phase velocity, (b) Interaction impedance.

The power flow per unit width corresponding to the n^{th} space harmonic in a planar helix with infinite width in the y -direction is given by:

$$P_{uw,n} = \frac{1}{2} \text{Re} \left[\int_x (E_{x,n} \cdot H_{y,n}^* - E_{y,n} \cdot H_{x,n}^*) dx \right]. \quad (31)$$

The total power flow is obtained by multiplying $P_{uw,n}$ by $2b$, i.e., the width in the y -direction:

$$P_n = P_{uw,n} \times 2b. \quad (32)$$

III. CALCULATED AND SIMULATION RESULTS

A. PH-SEC

The propagation constant of the fundamental space harmonic (β_0) is obtained by using the EDC method described in the previous section. The results of normalized phase velocity and interaction impedance for the fundamental space harmonic of the PH-SEC based on analysis are compared with the simulation results from CST eigenmode solver in Figs. 3-5 for different values of aspect ratio a/b . In each of these figures, the perimeter $4(a+b)$ of the PH-SEC is fixed as 9.6 mm, the results are given for three different pitch angles, $\psi = 2.5^\circ$, 5° , 7.5° , and the strip width is fixed as 20% of the pitch which is different for each pitch angle.

Fig. 7. Dispersion diagram of a PH-SEC with $a/b=1$, $a=1.2$ mm, $w/p_z=0.2$, and $a/p_z=1$

Fig. 3 shows the results for $a/b = 0.25$ and $a = 0.48$ mm, Fig. 4 shows the results for $a/b = 1$ and $a = 1.2$ mm, and Fig. 5 shows the results for $a/b = 4$ and $a = 1.92$ mm. For these different aspect ratios and pitch angles, the normalized phase velocity from analysis shows a good match with simulation results except at relatively low frequencies. It is well-known that the EDC method becomes less accurate at lower frequencies [14]. As expected, when the pitch angle decreases, the phase velocity also decreases. The interaction impedance from analysis also shows a good match with simulation results. The plots show that generally higher values of interaction impedance can be obtained from a PH-SEC by increasing the pitch angle.

Fig. 3 also includes the normalized phase velocity and interaction impedance of the PH-SEC obtained from the sheath-helix approximation with EDC [12]. The figure shows that the results from the tape-helix approximation with EDC provide a more accurate estimate compared to that from the sheath-helix approximation with EDC. From the results shown in Fig. 3 we observe that for $\psi=7.5^\circ$ the tape-helix model provides a maximum improvement in the phase velocity values of 20% at the lower frequency end and 4% at the higher frequency end over the sheath-helix model. The interaction impedance also shows similar percentage improvements.

To enable comparison of the calculated and simulated results at W-band frequency range, Fig. 6 shows the normalized phase velocity and interaction impedance of a PH-SEC with $a/b = 1$, and $a = 0.15$ mm for three different pitch angles ($\psi = 2.5^\circ, 5^\circ, 7.5^\circ$). The strip width of the PH-SEC is fixed as 20% of the pitch. Similar to the previous results, here also the normalized phase velocity from analysis shows a good match with simulation results except at relatively low frequencies. Moreover, the interaction impedance from simulation and analysis also show a reasonably good match. These results indicate that the analytical method can provide results for frequencies in the range of 100s of GHz.

The dispersion diagram for a PH-SEC with $a = b = p_z = 1.2$ mm and the strip width = 0.24 mm is given in Fig. 7. This diagram is obtained from the numerical solution of the analytical equations for frequencies even beyond the pi-frequency. The diagram shows the existence of pass bands and stop bands in the PH-SEC like other periodic SWSs.

Fig. 8. Comparison of normalized phase velocity for a rectangular tape helix with $b/a=10$, $p_z/a=2$, $w/p_z=0.2$ and $a=0.232$ mm.

Fig. 9. Comparison of normalized phase velocity for a rectangular tape helix with $b/a=1$, $p_z/a=1$, $w/p_z=0.1$ and $a=15.85$ mm.

The abovementioned figures show that the analysis presented here can provide accurate results for the PH-SEC for a wide range of aspect ratios and pitch angles.

B. Rectangular tape-helix

The analysis in this paper is also used to find the dispersion characteristics of rectangular tape-helix SWS. The results are compared with those from the tape-helix analysis of a rectangular tape-helix SWS reported in [9]. The analysis in [9] uses relatively complicated boundary conditions which result in a complex characteristic equation. Fig. 8 presents the normalized phase velocity for a rectangular tape-helix with $b/a = 10$, $p_z/a = 2$, $w/p_z = 0.2$, and $a = 0.232$ mm. The figure also includes the results reported in [9] for the same dimensions. Our method shows a better match with HFSS simulation results over a broader frequency range.

Fig. 9 shows the normalized phase velocity of a rectangular tape-helix with $b/a = 1$, $p_z/a = 1$, $w/p_z = 0.1$, and $a = 15.85$ mm. This figure also includes the results for the rectangular tape-helix reported in [9]. This figure indicates that the results from our method have a slightly better match with HFSS results at relatively high frequencies as compared to those reported in [9].

IV. CONCLUSION

Dispersion characteristics and interaction impedance of the planar helix slow-wave structure with straight-edge connections (PH-SEC) have been obtained using the tape-helix analysis. Effective dielectric constant (EDC) method is

incorporated with the tape-helix analysis of the infinitely wide planar helix to simplify the tape-helix analysis of the PH-SEC. The calculated results obtained from the proposed method for various aspect ratios and pitch angles are shown to have a good match with simulation results except at relatively low frequencies where the EDC method becomes less accurate. The proposed method is also used for obtaining the dispersion characteristics of the rectangular tape-helix; the results are more accurate over a broader bandwidth than the previously reported results based on more complicated tape-helix analysis. Further work is required to include in the analysis the effect of practical aspects such as dielectric support for the PH-SEC, finite strip thickness, vacuum tunnel, and metal envelope.

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