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Determination of stopband characteristics of asymmetrically loaded helix slow wave structures with Auxiliary Functions of Generalized Scattering Matrix (AFGSM) method

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A B S T R A C T

In this paper, a novel reformulated Auxiliary Functions of Generalized Scattering Matrix (AFGSM) method is presented for analyzing stopband characteristics of asymmetrically loaded helix Slow-Wave Structures (SWSs). In this method, the stopband problem of asymmetrically loaded helix SWS is reduced to the determination of zero transitions of $\bar{J}_{-1}$ and $\bar{R}_{-1}$ auxiliary functions in the vicinity of π-point frequency. Besides, Generalized Scattering Matrix (GSM) representations of a single turn of helix SWS are clearly expressed for different asymmetries which can occur with different ways due to angular offset of the rods, variations of support rod permittivity values and widths, angular offset of metal segments, variations in gap between helix to segment and segment width. In order to show the accuracy of the method, the proposed AFGSM method is verified with open literature. The applicability of the proposed method to analyze asymmetrically loaded helix SWS is quite simple and the method accurately determines Relative Stopband Bandwidths (RSBs) under different asymmetries.

1. Introduction

Helix Traveling Wave Tubes (TWTs) are used as microwave power amplifiers for communication and electronic countermeasure (ECM) systems when extremely broad bandwidth is required [1]. Main components of a Helix TWT are electron gun, helix slow wave structure (SWS), RF input/output couplers and collector. Helix SWSs dominantly affect RF performance of TWTs due to their important dispersion characteristics and therefore their analysis has been investigated in open literature with several methods in [1–8]. Fundamental elements of helix SWSs are typically sheath/-tape helix, metal envelope and dielectric support rods as depicted in Fig. 1. The helix is generally made of tungsten tape which is a relatively delicate structure and should also be supported strictly. On the other hand, thin dielectric support rods are used to avoid loading effects. The most commonly used dielectric materials are BeO and APBN to support helix SWSs. Three equally spaced dielectric support rods and helix are placed into the metal envelope. Additionally, helix SWSs can be loaded with metal segments in order to obtain better dispersion characteristics for broadband TWTs. These segments must also have perfect symmetric placements in the helix SWSs.

All these placements must be completed perfectly without asymmetry. Otherwise, asymmetry of any displacements of helix SWS elements give rise to stopband in the vicinity of π-phase point where fundamental forward and backward waves intersect. Furthermore, these asymmetries cause band edge oscillation and power holes which negatively affect the power performance of the TWT. Thus, the occurrence of this stopband due to asymmetrically loaded helix SWS is a critical issue for the design of broadband TWTs.

Effects of the asymmetry on the performance of the TWT are evaluated by stopband characteristics of helix SWS. To analyze stopband characteristics, several analytical methods based on Coupled Mode Theory (CMT) have been reported in [9–13]. Hinson and Lien in [9,10] analyze the helix SWS supported by dielectric rods in a metal envelope and assume the circuit as dispersionless and lossless which is limited both narrowband applications and low frequencies. Onodera's approach in [11] also considers a lossless circuit with metal segment loading. Datta et al. in [12] analyze the same structure by multireflection coupled mode analysis without metal segments. Recently, published paper by Datta et al. [13], which is based on multireflection coupled-mode analysis, brings

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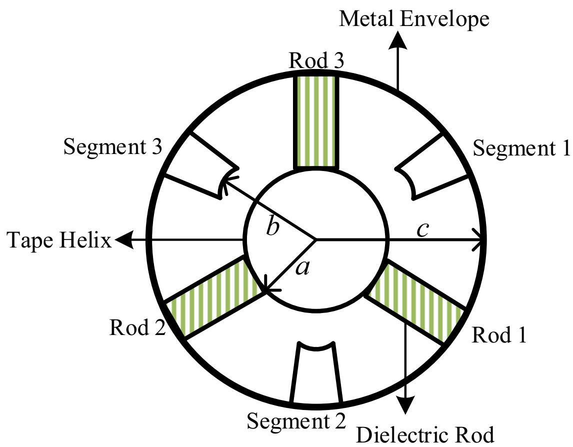

Fig. 1. Cross-section view of a typical helix slow wave structure of TWT.

the stopband analysis phenomena of helix SWS to an important point and strongly contributes to stopband analysis of helix SWS asymmetries including not only angular variation of dielectric support rods but also variations of dielectric constant of support rods, dielectric support rod width, angular position of metal segment, helix to segment gap and segment width.

Analysis of asymmetrically loaded helix SWSs is heavily based on CMT in the available literature. Therefore, CMT can be named as a conventional method in order to analyze asymmetrically loaded helix SWSs. Coupled Mode Theory used for analysis of forward and backward space-harmonics waves in the vicinity of π-point frequency of the helix SWSs needs uncoupled propagation constants of the forward and backward space harmonics in order to calculate coupled degenerate mode propagation constants [14–16]. In addition to this, total reflection coefficient has to be computed by using the multireflection approach to find coupling coefficient of coupled mode dispersion relation. In order to obtain coupled mode dispersion diagram, ladder circuit representation of helix SWS is used. It is important to say that equivalent circuit representation of one period of the helical SWS has to be $\beta p = \pi$ phase difference at the π-point frequency. Computation of total reflection coefficient of the helical SWS is required for CMT analysis at the π-point frequency.

A comprehensive Auxiliary Functions of Generalized Scattering Matrix (AFGSM) method presented in [17] is valid for periodic structures not only symmetric but also asymmetric unit cell configurations of periodic structures. AFGSM method has been proposed in [17] to determine the bandgaps of periodic structures (PSs) such as periodically dielectric loaded waveguides, photonic crystals and helix SWSs with their asymmetric unit cell configurations. The proposed method in [17] is based on the computation of the two auxiliary functions ($J_{\pm1}$) which are related with stored complex power in the unit cell (UC) and deducing the stopband of the periodic structures.

In this paper, we have reformulated AFGSM method in [17] in a different manner and developed quite simple and elegant auxiliary functions with respect to the functions given in [17]. This reformulation can be simply obtained with the aid of eigenvalue equation in terms of generalized scattering matrix of the unit cell of the periodic structure. Band edge conditions are forced on the eigenvalue equation. Novel functions developed in this study can be straightforwardly used to determine bandgaps of periodic structures. In the presented paper, we have investigated stopband characteristics of asymmetrically loaded helix SWSs of TWTs. The proposed reformulated AFGSM method uses the same ladder circuit representation of the helix SWS at the π-point frequency with Coupled Mode Theory. Besides, the presented method just only requires generalized scattering matrix of the unit cell of helix SWS. Therefore, GSM computation is sufficient to determine stopband characteristics of asymmetrically loaded helix SWS with AFGSM method differently from Coupled Mode Theory. Asymmetric cases of support rods of helix SWS for different scenarios and their effects on Relative Stop Bandwidth (RSB) are analyzed with the aid of AFGSM method. To the best of our knowledge, no attempt has been made with a similar approach to determine stopband characteristics of asymmetrically loaded helix SWSs. To this end, the proposed AFGSM method in this paper introduces a new perspective to analyze and design of helix SWS in contrast to conventional Coupled Mode Theory.

2. AFGSM theory for helix SWSs

A comprehensive AFGSM method is presented to the available literature to determine stopband characteristics of periodic structures. The method given in [17] is based on the analysis of stored complex power in the unit cell of the periodic structure. When it is assumed that one Floquet mode propagates along the unit cell and invoking band edge conditions, auxiliary functions ($J_{\pm1}$) are derived in [17] in terms of generalized scattering parameters (S_{11}, S_{21}, S_{22}) as given below for lossless and reciprocal periodic structure.

$$J_1 = 2\mathrm{Im}\{S_{11} + 2S_{21}\mathrm{Re}\{K_1\} + S_{22}|K_1|^2\} = 0 \tag{1}$$

$$J_{-1} = 2\mathrm{Im}\{S_{11} + 2S_{21}\mathrm{Re}\{K_{-1}\} + S_{22}|K_{-1}|^2\} = 0 \tag{2}$$

where

$$K_1 = \frac{1 - S_{21}}{S_{22}}, \quad K_{-1} = \frac{-1 - S_{21}}{S_{22}} \tag{3}$$

Proposed functions of J_1 and J_{-1} derived in [17] can be directly used for the bandgap analysis of periodic structures.

In this study, instead of focusing on complex power in the unit cell, we deal with eigenvalue equation of periodic structures with a different point of view. Eigenvalue equation of a nonsymmetrical unit cell of a PS can be written in terms of generalized scattering parameters of UC, given in [18] as below,

$$cos\theta = \frac{1 - S_{11}S_{22} + S_{21}^2}{2S_{21}} \tag{4}$$

For single Floquet mode propagation in unit cell, eigenvalue is defined as

$$\lambda_{1,2} = e^{\pm j\theta}, \theta = \beta p \in (0, \pi) \tag{5}$$

where β and p are Floquet phase factor and period of the UC. Stopbands of the unit cell occur at $\theta = 0$ and $\theta = \pi$ which correspond to the $\lambda = +1$ and $\lambda = -1$, respectively. When we substitute $\theta = 0$ and $\theta = \pi$ values in Eq. (4) we obtain

$$S_{11}S_{22} - (1 - S_{21})^2 = 0, \quad \text{for} \quad \theta = 0, \ \lambda = 1 \tag{6}$$

$$S_{11}S_{22} - (1 + S_{21})^2 = 0, \quad \text{for} \quad \theta = \pi, \ \lambda = -1 \tag{7}$$

In order to obtain proper functions as given in (1) and (2), we can take the imaginary and real part of Eqs. (6) and (7). Hence, imaginary and real part of (6) and (7) must be zero at the band edge frequencies for $\lambda = +1$ and $\lambda = -1$, respectively. Therefore, $\bar{J}_1, \bar{R}_1, \bar{J}_{-1}$ and $\bar{R}_{-1}$ auxiliary functions which correspond to the $\lambda = +1$ and $\lambda = -1$ band edge conditions can defined as

$$\bar{J}_{\pm1} = \mathrm{Im}\{S_{11}S_{22} - (1 \mp S_{21})^2\} = 0 \tag{8}$$

$$\bar{R}_{\pm1} = \mathrm{Re}\{S_{11}S_{22} - (1 \mp S_{21})^2\} = 0 \tag{9}$$