Analysis of metamaterial assisted helix slow-wave structure for Q-band

Raktim Guha[#1], S. K. Ghosh[#2]
[#]CSIR-Central Electronics Engineering Research Institute
Pilani-333031, Rajasthan, India
[1]raktim.guha01@gmail.com
[2]ghoshskdr@gmail.com, skghosh@ceeri.res.in

***Abstract*-This paper presents analysis of Q-band (39.5-47.5 GHz) helix slow-wave structure (SWS) supported by S-shaped metamaterial in a metal envelope and its advantage over its counterpart — conventional anisotropic helix SWS. S-shaped dual-band resonant metamaterial — printed on both the radial faces of the discrete dielectric support rods which are mirror image to each other, exhibit double negative and double positive metamaterial response after exciting with transverse electric and transverse magnetic mode, respectively, at Q band. Both the proposed and conventional SWSs are simulated in CST and cold parameters, namely, dispersion and interaction impedance characteristics have been compared. Performance of the proposed structure improves with enhanced transverse dimensions.**

***Keywords*: Helix slow-wave structure, S-shaped metamaterial, double negative metamaterial, interaction impedance, travelling-wave tube, geometry enhancement.**

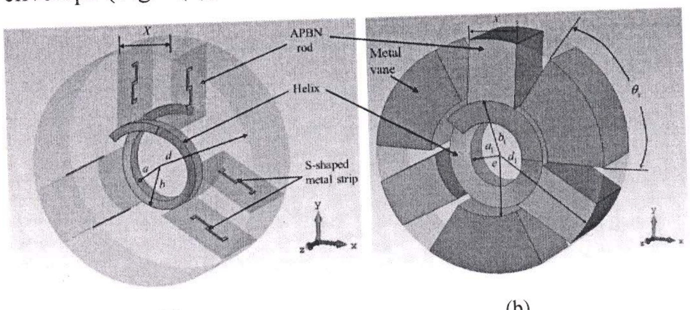
I. Introduction

A compact and light weight helix travelling-wave tube (TWT) with moderately high power and wide-bandwidth has been a topic of interest of the vacuum electron devices community for next-generation satellite systems with high data rate and high-resolution radar in Q-band [1]-[2]. However, to achieve enhanced performance over wide bandwidth, helix slow-wave structure (SWS) is loaded anisotropically — realized by projecting metal vanes radially inward from the metal envelope, to get flat-to-negative dispersion characteristic. But, with the increase in frequency, fabrication challenges arouses as transverse dimension of the structure decreases and hence, attempts are being made to increase transverse dimension with improved performance of the TWT, using left-handed meta materials [3].

A novel way has been proposed to enhance the geometry using the concept of multiband metamaterial response, and has been achieved by loading the helix SWS with dual-band resonant S-shaped MTM printed on both the radial faces of the discrete dielectric support rods which are mirror image to each other to reduce the bi-anisotropy [4], [5] (Fig. 1(a)). By suitably modelling the S-shaped metal-strip, double negative (DNG) and double positive (DPS) metamaterial response have been achieved over 39 to 50 GHz while excited with transverse electric (TE) and transverse magnetic (TM) modes, respectively. Over the wideband, the proposed SWS exhibit negative dispersion and higher interaction impedance with ~63% enhanced helix inner radius.

II. Proposed Structure

Position The proposed structure comprises of helix in a metal envelope supported by rectangular APBN dielectric rods printed with S-shaped metal-strip MTM on both of its radial faces which are mirror image to each other (Fig. 1(a)) modeled in CST [6]. Whereas the conventional structure comprises of helix supported by APBN rectangular dielectric rods in an anisotropic metal envelope, realized by providing wedge-shaped metal vanes projecting radially inward from the envelope (Fig. 1(b)).



(a) (b)

Fig. 1. Single-turn helix in a metal envelope (a) helix supported with metamaterial in a metal envelope (proposed structure) and (b) helix supported with dielectric support in an anisotropic metal envelope. (a = 0.68 mm, b = 1.22×a, d = 3×a, X = 1.45×a, ε_r = 5.1 (APBN); a_1 = 0.25 mm, b_1 = 1.22×a_1, d_1 = 3×a_1, X_1 = 1.45×a_1, e = 1.3×a_1, θ_v = 40°).

III. Results

Unit cell of S-shaped metal-strip printed on both the radial faces, mirror image to each other, of the curved rectangular dielectric support rod (Fig. 2) excited by TE and TM mode to retrieve the effective relative permittivity and permeability (Fig. 3). The retrieved property of the S-shaped metamaterial exhibits DNG and DPS responses within the desired frequency band 39-50 GHz.

Both proposed and conventional SWSs (Fig. 1) have been simulated using CST-Eigen mode solver [6] to obtain phase (Fig. 4(a)); normalized phase velocity (v_p/c) and interaction impedance K (Fig. 4(b)). Shaded area defined operating frequency range (39.6-47.5 GHz) of the desired mode (mode 4). Negative dispersion has been achieved using the proposed structure (Fig. 4(b)). Further, the v_p/c and K and the physical dimensions of both the structures have been compared. The proposed structure exhibits same dispersion characteristics with ~63% enhanced inner radius of the helix than the conventional SWS. Thus, one can increase the beam radius and power handling capability of the structure and reduces fabrication complexity at Q-band. Also the proposed SWS exhibits negative dispersion without metal vanes reducing fabrication complexity.

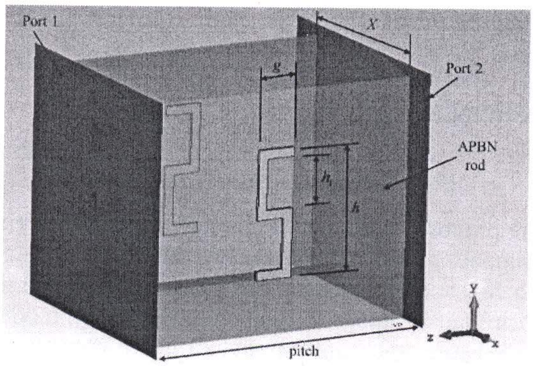
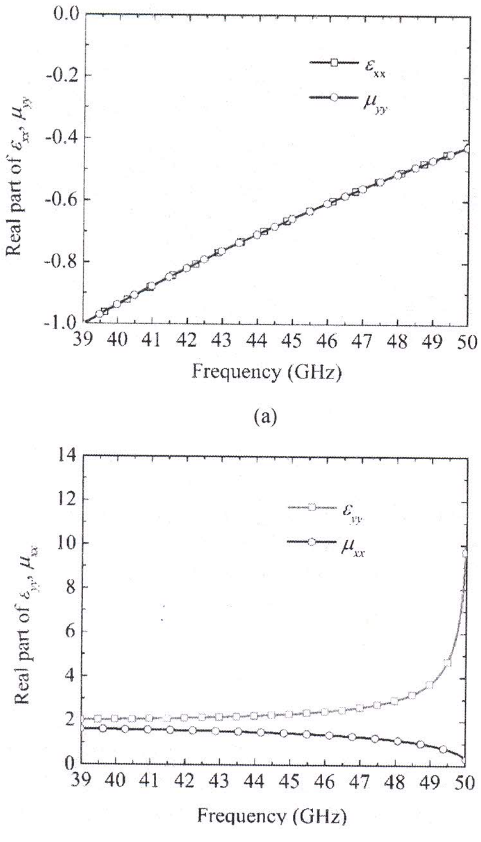
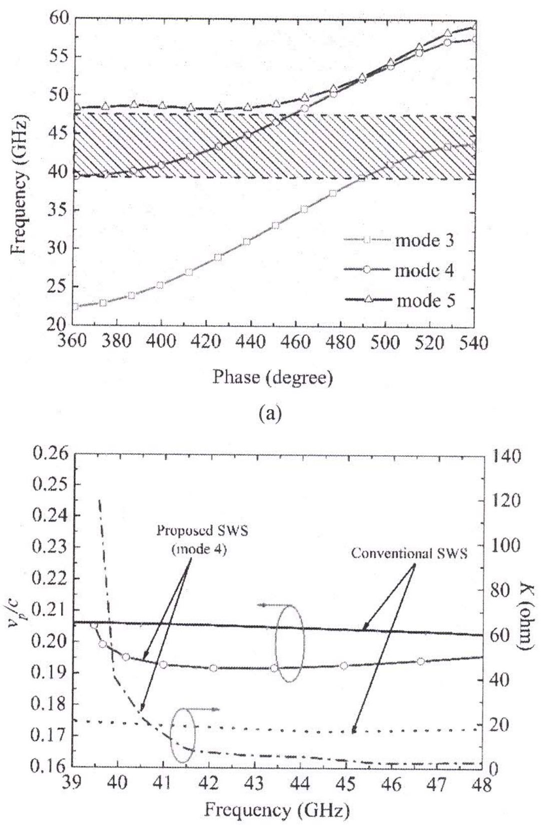


Fig. 2. Unit cell of S-shaped metamaterials printed on both the radial faces, mirror image to each other, of the rectangular dielectric support rod (APBN, $\varepsilon_r = 5.1$) ($g = 0.2$ mm, $h = 0.7$ mm, $h_1 = 0.275$ mm, $X = 1.45 \times a$, pitch $= 2.3 \times a$, $a = 0.68$ mm).



(b)

Fig. 3. Extracted relative permittivity and permeability of S-shaped MTM excited by (a) TE along x-direction and (b) TM mode along y-direction.



(b)

Fig. 4. (a) Phase-frequency response; and (b) v_p/c and K versus frequency characteristics of the proposed SWS and conventional SWS. Shaded area defined operating frequency range (39.6-47.5 GHz) of the desired mode (mode 4).

IV. Conclusion

In this simulation based study we have proposed a novel S-shaped MTM assisted helix SWS which proves to be an alternative to the conventional anisotropic vane loading of the helix to provide dispersion control at Q-band with enhanced physical dimensions which further improves the power handling capability of the SWS. Thus the proposed structure has potential application in next-generation satellite systems with high data rate and high-resolution radar in Q-band.

References

[1] B. Qu, X. Liang, C. Guo, Y. Shang and J. Feng, "Development of 45W Q-band Space Qualified TWTs," *J. of Electr. Eng. and Electron. Technol.*, vol. 7, no.3, pp. 1-5, Oct. 2018

[2] C. K. Chong , D. A. Layman, W. L. McGeary, W. L. Menninger, M. L. Ramay, and X. Zhai "Q/V-Band High-Power Uplink Helix TWT for Future High-Data-Rate Communications," IEEE Trans Electron devices, vol. 65, no. 6, pp. 2201-2205, June 2018.

[3] R. Guha , A. K. Bandyopadhyay, A. K. Varshney, S. K. Datta, and B. N. Basu, "Investigations into Helix Slow-Wave Structure Assisted by Double-Negative Metamaterial," IEEE Trans. Electron Devices, vol. 65, no. 11, pp. 5082-5088, Nov. 2018.

[4] H. Chen, L. Ran, J. Huangfu, X. Zhang, and K. Chen, "Left-handed materials composed of only S-shaped resonators," Phys. Rev. E, vol. 70, no. 5, p. 057605, Nov. 2004.

[5] R. Marqués, F. Mesa, J. Martel, and F. Medina, "Comparative Analysis of Edge- and Broadside-Coupled Split Ring Resonators for Metamaterial Design—Theory and Experiments," IEEE Trans. Antennas and Prop., vol. 51, no. 10, Oct. 2003.
[6] CST AG, Darmstadt, Germany. CST STUDIO SUITE. Accessed: 2019. [Online]. Available: www.cst.com.