Preliminary Analysis of a Folded Waveguide Slow-Wave Structure for 160GHz Traveling Wave Tube Amplifier

Surya Prasath C[1], Ipsit Ray, Sneka J, Matheshwara A. S., Richards Joe Stanislaus[2]
School of Electronics Engineering
Vellore Institute of Technology Chennai
Chennai, India
[2]richardsjoes@gmail.com

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***Abstract*—This paper presents the preliminary analysis of a folded waveguide (FWG) slow wave structure (SWS) for 160GHz traveling wave-tube amplifier. Traveling wave-tube amplifiers operational in the D band of the millimeter wave frequencies are the apt candidates for their application in the point-to-point backhaul communication of 5G and above networks, and in the inter-satellite communication in space. The dispersion analysis of the unit cell of the FWG SWS presented in this paper effectively describes the dependence of the critical design parameters, namely the operational frequency range, bandwidth, and phase velocity on the dimensional variables. An operational bandwidth of 20GHz ranging from 155GHz-175GHz has been successfully obtained with a RF phase velocity of 0.244 times velocity of light in this paper.**

Keywords—folded waveguide, slow wave structure, dispersion analysis, D band, traveling wave tube amplifier.

I. Introduction

Millimeter wave microelectronic devices find their applications in inter-satellite and deep space communications, radars, ultra-high-resolution imaging and in backhaul communication of the 5G and beyond applications [1-5]. The conventional helix traveling wave tube amplifier [6] cannot be supported as amplifier in the millimeter wave regime as the fabrication of helix at these frequencies are highly challenging due to their small size and this results in extremely fragile structure which are not suitable space applications. The alternative slow wave structures proposed in recent years include folded wave-guide, staggered-double, ridge loaded, sine-waveguided, double corrugated structures, over-moded coupled cavity, etc [1-5, 7-10].

A volume mode traveling wave tube amplifier employing photonic band gap structures in SWS was proposed in [2] with the over-moded coupled cavities. The particle in cell simulation of a staggered double vane slow wave structure was presented in [3] for W band TWTA. In [4], the design methodology for the design of folded waveguide SWS is proposed, and in [5], the particle in cell simulations for 220GHz FWG SWS is presented. Similar analysis have been performed for FWG SWS in [7-9] and in [10], a staggered double vane SWS with arc shaped beam tunnel is proposed for millimeter wave applications.

In this paper, the dependence of the dispersion parameters, namely the phase velocity, operational range of frequencies and the operational bandwidth are present for varying structural dimensions. Section II of this paper discusses the variables used in the representation of one Unit cell. In section III, the dependence of the dimensional parameters on the dispersion characteristics are studied. The dispersion parameters of an optimally modelled unit cell for 160GHz FWG SWS is presented in section IV. Section V concludes the paper with the mention of the future work to be carried on from this paper.

II. Unit Cell

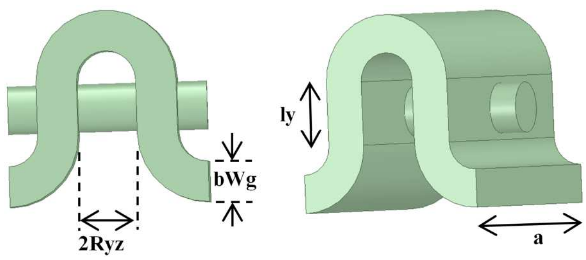


Fig. 1 2D and 3D view of one unit cell of Folded waveguide slow wave structure

Fig. 1 displays one unit cell of the folded waveguide slow wave structure. A cylindrical beam tunnel is proposed in this structure which supports an electron beam of circular cross section. The folded waveguide's cross-sectional dimensions include the variables "a" and "bWg", which indicate the width and height of the rectangular waveguide. The inner curve radius is represented as "Ryz" and the length of the vertical section of the waveguide is represented by "ly". Through the vertical section of the slow wave structure, the beam tunnel passes orthogonally. One pitch distance, "p" thus consists of a distance of 4Ryz+2bWg.

III. Effect of Dimensions on Dispersion Characteristics

The effect of the dimensions of the unit cell on the operational frequencies, bandwidth and the phase-velocity of the RF signal are discussed in this section.

TABLE I. Reference Values

Description	*Variable Name*	*Value (mm)*
Waveguide width	a	1.6
Waveguide height	bWg	0.13
Vertical section length	ly	0.24
Folded Waveguide inner radius	Ryz	0.1

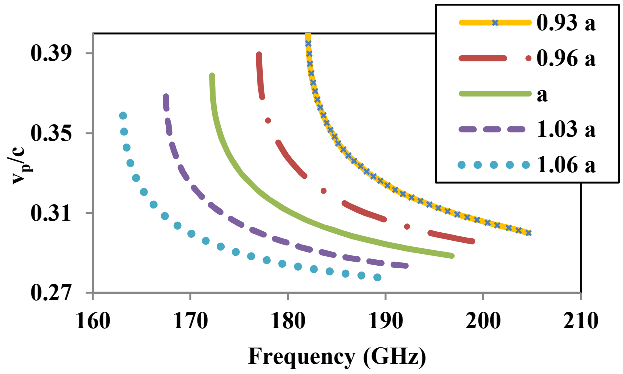


Fig. 2 Effect of waveguide width, a, on the dispersion characteristics

Fig. 2 displays the effect of the waveguide width, a, on the dispersion plot. The x-axis represents the frequency in GHz and the y-axis represents the normalized phase velocity of the RF signal in the SWS. The dispersion characteristics of the reference structure is plotted in green and the corresponding values are listed in table I. From Fig. 2, it can be observed that, on increasing the width of the waveguide, the operational frequencies are shifted to the lower side, which is in-line with the characteristic feature of a rectangular waveguide. The flatness of the dispersion curve also increases as the width of the waveguide is increased.

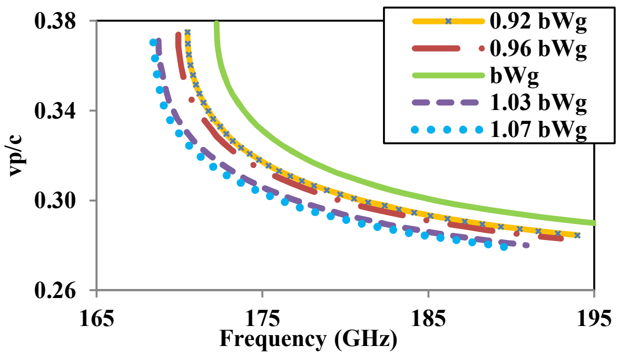


Fig. 3. Dispersion characteristics of the unit cell with increasing waveguide heights(b)

The dispersion characteristics of the unit cell with increasing waveguide heights are plotted in Fig. 3. It can be observed that minimal changes in dispersion characteristics are observed on changing the height of the rectangular waveguide. This essentially alters the pitch distance and also the amount of the exposure of the electron beam and the RF electric field. For higher values of the waveguide height, the dispersion plot converges to a slightly lower operational frequencies and at slightly reduced RF phase velocity.

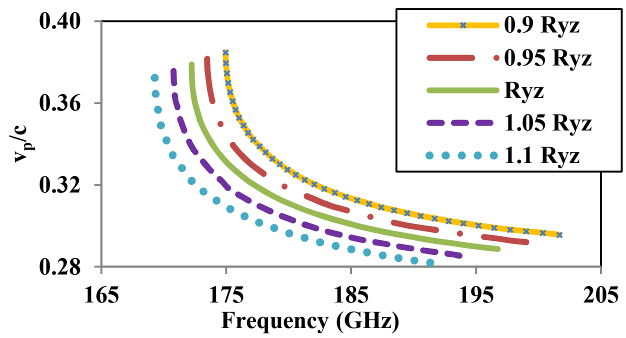
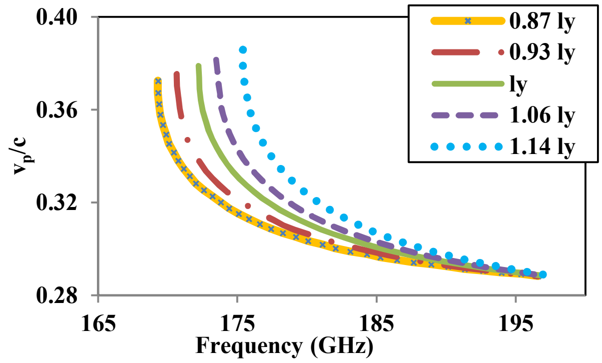


Fig. 4. Effect of inner radius of the FWG, Ryz, on the dispersion characteristics

Fig. 4 plots the effect of the inner radius of the FWG, Ryz, on the dispersion characteristics of the FWG unit cell. The complete range of operational frequencies are left shifted(reduced) when the bent radius in increased. Similarly, the phase velocity of the RF signal reduces as the bent radius is increased. There is minimal offset in the bandwidth for different inner radii.



Fig, 5. Dispersion characteristics of unit cells with vertical sections different lengths ly of the FWG.

In Fig. 5, the effect of the length of the vertical section, ly, on the dispersion characteristics are plotted. When the length ly is increased, the flatness reduces in the lower end of the operational frequencies, with the uppermost frequency point as fixed. This suggests that, for lower values of the length of the vertical section, a much wider bandwidth is achievable with the uppermost operational frequency as constant. The phase velocity is also increased when the value of ly is increased.

IV. Dispersion Characteristics of 160GHz FWG SWS

On understanding the effects of the dimensional parameters on the dispersion characteristics, an optimal design of a unit cell is obtained for the dispersion plots.

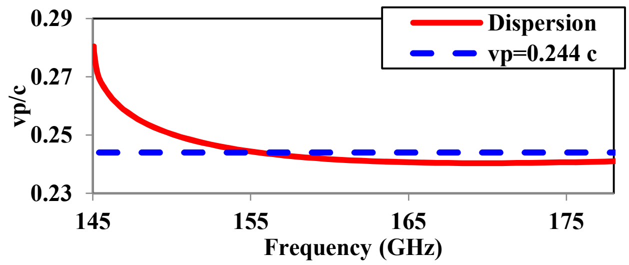


Fig. 6 Dispersion plot of the proposed structure.

TABLE II. Dimensions of 160GHz FWG SWS

Variable normalized to one pitch(p)	*Value (ratio)*
a/p	3.45
bWg/p	0.26
ly/p	0.31
Ryz/p	0.12

Fig. 6 displays the dispersion plot of the optimized structure with a reference DC beam line of 0.244 times velocity of light, which is highlighted in blue dashed lines.

The region around the DC beam line correspond to the operational bandwidth of the SWS. The normalized values of the dimensions of the proposed unit cell of the SWS are listed in Table II.

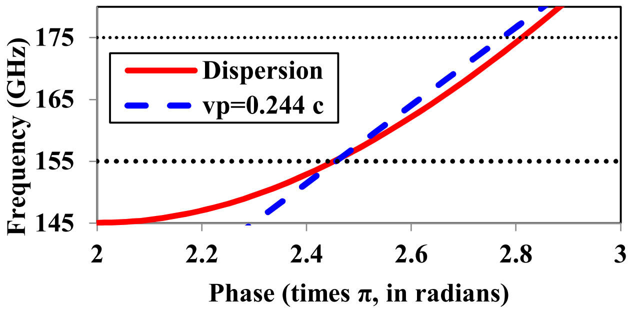


Fig. 7 Phase shift per pitch corresponding to its operational frequencies.

Fig. 7 displays the phase shift per pitch corresponding to its operational frequencies. The x-axis represents the phase shift per pitch distance, which has to be multiplied by π radians. A DC beam line of 0.244*c is also plotted as dashed line. An estimated operational frequency range of 20GHz has been observed in the dispersion plot. An interaction impedance of less than 10 ohms was observed in the operational bandwidth.

V. CONCLUSION

In this paper, the preliminary analysis of a folded waveguide slow wave structure has been performed and the effect of the dimensional parameters on the dispersion characteristics is studied. An operational band of 20GHz has been successfully obtained from 155GHz to 175GHz for an optimally modelled structure. The results will be implemented in the design of the complete SWS with the attenuator design and the RF couplers in the future.

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