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METAMATERIAL MEDIATED INVERSE CHERENKOV ACCELERATION

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Abstract

In this paper we examine the effect of introducing an Electromagnetic metamaterial into a Travelling Wave structure to mediate inverse Cherenkov acceleration. Electromagnetic metamaterials are artificial materials that consist of macroscopic structures that yield an effective permittivity and permeability less than zero. The properties of metamaterials are highly frequency dependent and give rise to very novel dispersion relationships. We show that the introduction of a specifically designed metamaterial into the interaction region gives rise to a novel dispersion curve yielding a unique wave-particle interaction. We demonstrate that this novel wave-particle interaction gives rise energy exchange from wave to beam over an extended interaction regime. We also discuss the benefits and issues that arise from having a metamaterial in a high vacuum high power environment with a specific focus on the issue of loss in metamaterial structures

INTRODUCTION

In this paper we consider the application of metamaterials to Traveling Wave Tubes (TWT). The TWT proposed in the 1940's by Kompfner [1] remains the driving technology for many applications ranging from communications to radar. The interaction between electron beam and EM field results in an energy transfer from beam to wave. To date four papers [2][3][4][5] have considered metamaterials in TWTs, first three of them used metamaterials to line the side of the structure to minimise losses and increase efficiency, while the 4th paper [5] used metamaterial along the waveguide mode propagation path.

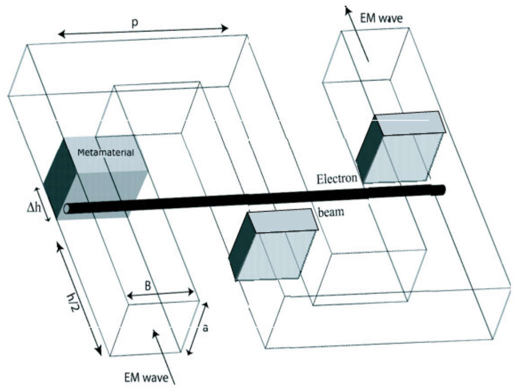

Figure 1: The TWT structure, consisting of folded waveguide with a metamaterial insert, the electron beam passes through the middle of the structure

In this paper, we introduce metamaterial at the interaction region between beam and wave, controlling the Folded waveguide travelling wave tube (FWTWT) dispersion relationship via the metamaterial, to define a unique beam-wave interaction, triggering a novel gain-frequency phenomena.

METHODOLOGY

For effective energy transfer between beam and EM wave the phase velocity (determined by the dispersion) of the wave must approximately match the velocity of the electron beam. In the conventional FWTWT this is achieved via the periodicity of the folded waveguide [6] to slow down the wave, generating Spatial Harmonics Wave Components [5] parallel to the beam. The SHWC interact with the beam resulting in energy transfer. By inserting a metamaterial, of length Δh into the waveguide at the point of interaction between wave and beam; And to ensure that the phase of the EM field is the same at each point where wave and beam interact, the wave takes the long path around the folded wave guide, hence the period in the beam frame of reference is half the geometrical period of the structure shown in figure 1. This phase shift results in a propagation constant γ_n. Rearranging eqn.1 yields the dispersion relationship, eqn.2;

$$\gamma_n = \beta_0 \frac{p+h-\Delta h}{p} + \beta_{mm}(\omega)\frac{\Delta h}{p} + (2n+1)\frac{\pi}{p} \qquad (1)$$

$$\omega = \sqrt{c^2\left(\gamma_n - \left((2n+1)\frac{\pi}{p} + \beta_{mm}(f)\frac{\Delta h}{p}\right)\right)^2 \left(\frac{p}{p+h-\Delta h}\right)^2 + \omega_c^2} \qquad (2)$$

Refer to figure 1 for the corresponding length representation p, Δh, h in the eqn. 1 and eqn. 2 .The metamaterial structure the dispersion now exhibits a frequency material dependence, due to the $\beta_{mm}(f) = c^{-1}\sqrt{\omega^2 \varepsilon_r(\omega)\mu_r(\omega) - \omega_c^2}$;the phase constant of the metamaterial slab. Hence for a given form of $\varepsilon_r(\omega)$ and $\mu_r(\omega)$ we can define a unique dispersion curve. The form of $\varepsilon_r(\omega)$ and $\mu_r(\omega)$ is specified by careful design of the metamaterial to give additional control over the dispersion. The presence of the metamaterial has a marked effect on the dispersion of the SHWC, in particular the turning point at 9.7 GHz in the dispersion in figure (2a) which relates to the start of the regime where the metamaterial has both $\varepsilon_r(\omega)$, $\mu_r(\omega)$ <0 which is named as double negative regime [DNG]. For frequencies below the DNG point wave propagation does not occur due to both the effect of single negative $\varepsilon_r(\omega)$, high attenuation and the waveguide cut-off frequency.

The dispersion curve of each harmonic can be considered as consisting of two branches, "left" and "right" of the phase constant associated with the empty waveguide cut-off frequency. In conventional FWTWTs, the group velocity ($v_g = \partial\omega/\partial\beta$) which indicates the direction of power flow, in the left branch is $v_g<0$, while in the right branch is $v_g>0$. To determine the power transfer from beam to wave [5].

$$\Delta P = -\frac{1}{2}\frac{d}{d\gamma}\left\langle \Delta\gamma_1^{\,2}\right\rangle m_0 c^2 N \qquad (3)$$

$\Delta\gamma_1$ relates to the classical spontaneous power spectrum from the beam, where the electron beam consists of N electrons entering the system every second. The complexity of the full form of ΔP requires a numerical approach to calculation; a full derivation will follow in a future publication. With a change of variable and via substitution of the above terms we can express the change in power as;

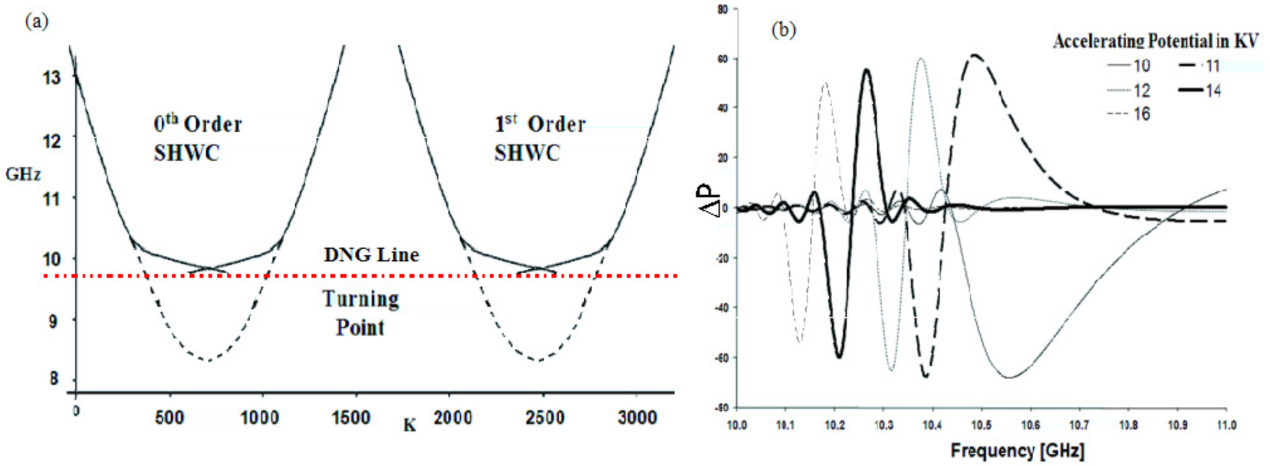

Figure 2: (a). Zeroth and first order SHWC dispersion curves, the solid line show the dispersion for the metamaterial TWT and the doted lines shows the dispersion for the conventional TWT; (b) Increase in EM power due to interaction with an electron beam, for different electron beam energies.

$$\Delta P = \frac{\omega^2\mu}{\beta_0}\frac{L^3}{2ab}Z^2\frac{d}{dX}\left(\frac{\sin^2(X)}{X^2}\right)\frac{c}{\gamma^3}\frac{1}{v_e^{\,3}}mc^2\, I_b/e \qquad (4)$$

$$Z = \frac{e}{mc^2}\frac{b}{p}\sin c\left(\beta_n'\frac{b}{2}\right)$$

$$\gamma = 1 + \frac{V_{acc}}{mc^2}$$

$$X = \left(\frac{\omega}{v_e} - \beta_n'\right)\frac{L}{2}$$

This form introduces the beam current *(I_b)* and the voltage though which the beam has been accelerated *(V_{acc})*.The sign of X is determined by the differences in velocity between wave and beam, which for $X<0$ indicates that initial the beam velocity is greater than the wave velocity. When the beam has higher velocity energy is exchanged from beam to wave until the velocities synchronism. Figure (2b) is a plot of eqn. (4) for several different V_{acc}.Where maximum energy exchange occurs for $X = -1.3$. As expected by design the largest ΔP occurs for an accelerating voltage of 11kV at 10.5GHz. X determine on $\varepsilon_r(\omega)$ and $\mu_r(\omega)$ and how when $X \geq 0$ energy gain from wave to beam.

CONCLUSION

This paper demonstrates that a metamaterial FWTWT offers an additional factor to controlling the gain-frequency characteristics, compared to the conventional FWTWT where the characteristics depend on the waveguide dimensions. Figure 3, the change in power between wave and beam, shows that as the accelerating potential is increased the frequency at which maximum energy exchange is achieved is shifting towards lower frequency. Although we note that even for large differences in accelerating voltage the frequency shift is small, this offers a precise way to tune the frequency of operation. The disadvantages are that the design is bandwidth limited, and highly dependent on the metamaterial used. Inherent ohmic losses associate with the MM are unavoidable. Future work in this area is to consider the use of a MM which offers a broadband of negative behavior, and a full discussion on the derivation of eqn. (4).

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