METAMATERIAL-BASED LINEAR ACCELERATOR STRUCTURE

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Abstract

Negative refraction metamaterials (NR MTM) have been developed at microwave, THz, and optical frequencies. Accelerator-relevant applications, such as measuring reversed Cherenkov radiation in a NR MTM, have been demonstrated. Here we propose a MTM based linear accelerator structure. The MTM is built as an array of complimentary split-ring resonators cut in two metallic plates. The accelerating electron bunch traverses between the plates. It is shown that the complimentary MTM (C-MTM) has negative permittivity and permeability. This allows one to build the C-MTM structure narrow and, therefore, provide good coupling to the electron beam and a high gradient. The operating mode's properties and standard accelerator parameters (R/Q, accelerating gradient, etc.) of the proposed structure are reported.

INTRODUCTION

Advanced accelerators are under development including plasmonic accelerators [1] to achieve high gradient acceleration at THz frequencies. An advanced photonic crystal based linear accelerator [2] has demonstrated high gradient at microwave frequencies (17 GHz) and is promising for higher order mode (HOM) wakefield damping. Metamaterials (MTM's) [3] have been proposed as photonic crystals made of sub-wavelength cells with magnetic response [4]. MTM's built for microwave applications exhibit the properties of plasmonic structures at THz frequencies [5]. Since high power microwave sources are available for accelerator applications, it is worth testing a microwave MTM-based accelerator structure as a prototype of the plasmonic accelerator structure.

Microwave MTM's are shown to be useful for filters and patch antennas [3]. Microwave MTM's are also of interest for applications in accelerators. In a recent accelerator related experiment [6] the reverse Cherenkov radiation of an electron bunch in a MTM was observed.

Most microwave MTM's comprise of resonant metallic structures (e. g. split-ring resonators [4]). Recently, a new class of complimentary metamaterials (C-MTM) [7] has been introduced and tested [8]. In this paper, a C-MTM designed at microwave frequencies is proposed as a linear accelerator structure. A microwave MTM based accelerator operating at microwave frequencies could serve as a prototype of a MTM based THz plasmonic accelerator.

METAMATERIAL STRUCTURE

The proposed accelerator structure (Fig. 1) is a C-MTM built of complimentary split-ring resonators (C-SRR's) [3], [7]. The C-SRR's are cut in a metal plate. The C-SRR patch plates are set parallel forming a waveguide. The mode of this waveguide has the electric field component along the waveguide symmetry plane. This longitudinal electric field is used for acceleration of the electron beam traveling down the symmetry plane of the waveguide. Earlier work [9] on C-SRR waveguides demonstrated the possibility of transmitting TEM-like modes through extremely narrow waveguides. Here we demonstrate that accelerator relevant TM-like modes are also supported by C-SRR based waveguides. Such an extremely narrow waveguide is attractive for electron acceleration because the shunt impedance and, therefore, acceleration gradient are enhanced.

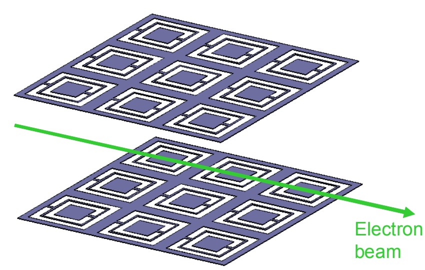

Figure 1: C-MTM used as accelerator structure.

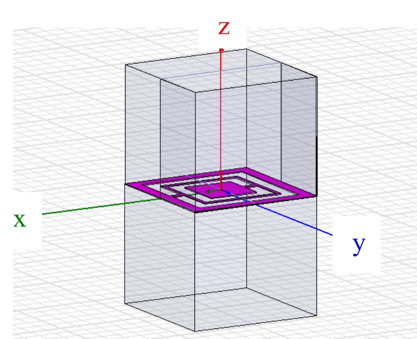

Figure 2: Cell used for HFSS simulations.

In this paper, we study the properties of the accelerating structure based on a C-MTM. The frequency and dimensions are not specific for a particular experiment. The design can be scaled for the frequency of 17 GHz suitable for experiment at MIT [2]. To study the C-MTM properties we conducted HFSS [10] simulations of an infinite C-MTM that consists of an infinite number of C-SRR patches set parallel to each other. To simulate the modes in this C-MTM we use only one cell of the C-MTM (Fig. 2). The C-SRR of width b=8 mm is in the center of the cell. The cell is of height d=12.8 mm. The H-wall boundary conditions are set at the top and bottom sides. Along the x and y directions, the phase advance boundary conditions are set. In the y-direction, the phase advance is 0 between the sides of the cell. Therefore, the mode uniform in the y-direction is simulated. The modes propagating in the x-direction are calculated. The phase advance in the x-direction between the sides of the cell has been varied from 0 to 180^o to calculate the dispersion. The cell shown in Fig. 2 can be translated in both x and y directions and also mirrored in the H-walls. The H-wall boundary condition is set to find the mode with the longitudinal electric field E_x in that plane. In Fig. 1, this plane corresponds to the symmetry plane of the waveguide.

The C-SRR parameters are listed in Table 1. The lower order modes in the C-MTM are calculated. Fig. 3 shows dispersion of these modes (the frequency as a function of the phase advance). The mode that can be used for acceleration exists between 5.33 GHz and 5.65 GHz (triangles in Fig. 3). It has negative dispersion: the group velocity is negative and opposite to the phase velocity. The mode has an accelerating field E_x and transverse electric E_z and magnetic H_y fields. The field distribution is plotted in Fig. 4. We classify this mode as a LP_{01} mode. In contrast to the rectangular waveguide mode, the longitudinal field E_x does not vanish at the waveguide wall because of the vacuum slits. The other mode (diamonds in Fig. 3) has no cutoff, it is a slow wave. It has the same field components, however, no longitudinal electric field at the symmetry plane.

Table 1: C-SRR Parameters

Width	8 mm
Outer ring slot length	6.6 mm
Slot width	0.8 mm
Inner ring slot length	4.6 mm
Split width	0.3 mm
Thickness	0.05 mm

METAMATERIAL PROPERTIES

The constitutive parameters of a MTM – effective permittivity and permeability – can be determined numerically using a simulation of one cell of the MTM shown in Fig. 2. The cell dimensions are b in the x- and y-directions and d – in the z-direction. We consider the waves with three components E_x, E_z, and H_y. We integrate Maxwell's equations over the cell and determine the averaged fields and constitutive parameters.

The effective constitutive parameters retrieved using the HFSS simulations are plotted in Fig. 5 as functions of frequency. The C-MTM can be modeled as a medium with the effective permittivity

$$\bar{\varepsilon}_{eff} = 1 - F\frac{\omega^2}{\omega^2 - \omega_0^2} \qquad (1)$$

In this model, the effective permittivity is infinite at the resonance frequency $\omega_0=2\pi f_0$, where f_0=5.33 GHz (Fig. 3), and equal to zero at the cutoff frequency $f_0/(1-F)$ =5.65 GHz, therefore, F=0.11. The medium effective permittivity presented by Eq. (1) and plotted in Fig. 5 (dashed line) is close to the numerically retrieved permittivity only near the cutoff frequency.

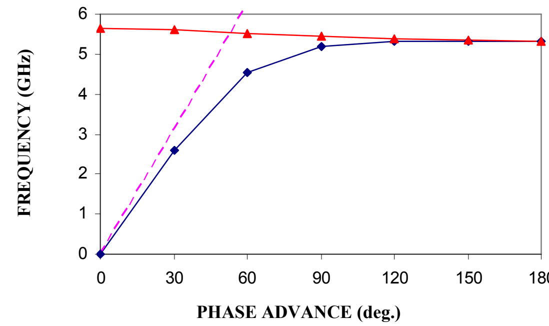

Figure 3: Dispersion of waves in the C-MTM: accelerating mode (triangles) and slow wave (diamonds).

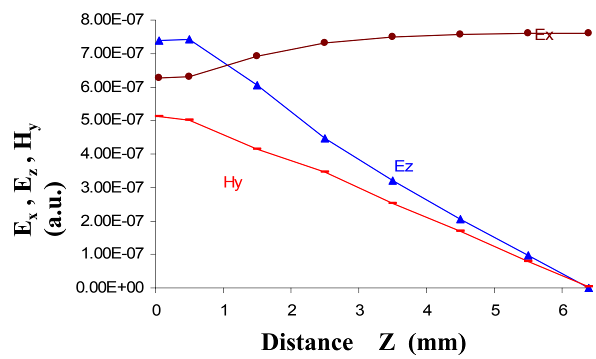

Figure 4: Field distribution in the C-MTM accelerator mode.

ACCELERATOR PARAMETERS

The operating point is chosen for the phase advance of 55^o, the frequency is 5.52 GHz. The accelerating gradient is calculated using HFSS. The gradient G as a function of power P can be expressed as

$$G\left[\frac{MV}{m}\right] = K\sqrt{P[MW]} \qquad (2)$$

where the coefficient K=4.9 for this configuration. It scales as frequency, so K=15 for a 17 GHz accelerator design. Note that K=25 for the 17 GHz PBG accelerator structure at MIT [2]. The gradient can be represented as

$$G = \sqrt{\frac{r_s}{Q}\frac{\omega}{V_g}P}\ , \qquad (3)$$

where r_s is the shunt impedance, V_g is the group velocity, and Q is the cell Q-factor. Therefore, r_s/Q =6.2 kΩ/m. It scales to 18 kΩ/m for a 17 GHz structure, and it is 23 kΩ/m for the PBG structure [2].

The MTM-based accelerator shown schematically in Fig. 6 has new features as compared to a conventional linear accelerator. Since the accelerating mode has negative dispersion, the input coupler is downstream as shown in Fig. 6. At microwave frequencies, the input and output couplers can be optimized. The couplers should be replaced by leaky wave antennas [11] in the MTM-based plasmonic accelerator operating at THz frequencies.

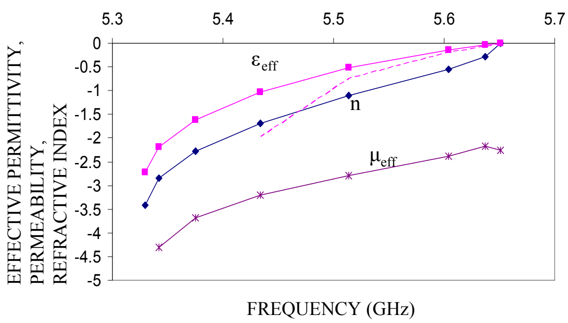

Figure 5: C-MTM effective permittivity, permeability, and refractive index extracted from simulation. Dashed line is the effective permittivity expressed by Eq. (1).

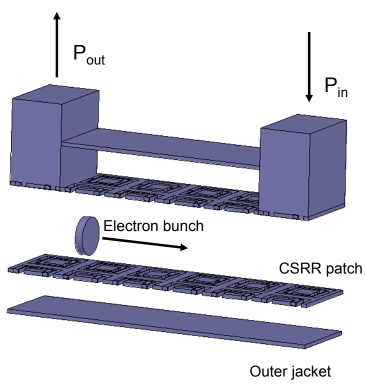

Figure 6: C-MTM-based accelerator schematic.

CONCLUSIONS

A C-MTM-based linear accelerator is proposed for operation at microwave and THz frequencies. The properties of C-MTM are studied at microwave frequencies using HFSS simulations. It is shown that the C-MTM has negative permittivity and permeability. This allows one to build the C-MTM structure narrow and, therefore, provide good coupling to the electron beam and a high gradient. The C-MTM-based accelerator can be tested at the frequency of 17 GHz at MIT. It can be a prototype of a plasmonic accelerator operating at THz frequencies.

ACKNOWLEDGMENTS

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REFERENCES

[1] S. Kalmykov, O. Polomarov, D. Korobkin et al., Phil. Trans. R. Soc. A 364 (2006) 725.
[2] E. I. Smirnova, A. S. Kesar, I. Mastovsky et al., Phys. Rev. Lett. 95 (2005) 074801.
[3] R. Marques, F. Martin, M. Sorolla. Metamaterials with Negative Parameters. Theory, Design, and Microwave Applications. Wiley-Interscience, John Wiley & Sons, Inc., Hoboken, New Jersey, 2008.
[4] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Techn. 47 (1999) 2075.
[5] M. A. Shapiro, G. Shvets, J. R. Sirigiri, and R. J. Temkin, Opt. Lett. 31 (2006) 2051.
[6] S. Antipov, L. Spentzouris, W. Gai et al., J. Appl. Phys. 104 (2008) 014901.
[7] F. Falcone, T. Lopetegi, M. A. G. Laso et al., Phys. Rev. Lett 93 (2004) 197401.
[8] H.-T. Chen, J. F. O'Hara, A. J. Taylor et al. Opt. Express 15 (2007) 1084.
[9] R. Liu, Q. Cheng, T. Hand et al., Phys. Rev. Lett. 100 (2008) 023903.
[10] High Frequency Structure Simulator, www.hfss.com, Ansoft Corporation, Pittsburg, PA, USA.
[11] T. Tamir and A. A. Oliner, Proc. IEEE 51 (1063) 317.