LA-UR-

09-04087

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Intended for: 34th International Conference on Infrared, Millimeter, and
Terahertz Waves, Busan, Republic of Korea, September 21 –
25, 2009.

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A Proposed Measurement of the Reverse Cherenkov Radiation Effect in a Metamaterial-Loaded Circular Waveguide

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Abstract—We have recently proposed an experiment on verification of the Reverse Cherenkov Radiation (RCR) effect in a Left-Handed-Material-loaded waveguide [1]. Applications of the RCR effect may range from novel higher-order-mode suppressors in microwave and millimeter-wave sources to improved particle detectors for satellite non-proliferation missions. The experimental configuration includes a circular waveguide filled with an artificial metamaterial with simultaneously negative permittivity and permeability, in which the electromagnetic wave with a frequency of 95 GHz will interact with an electron beam. We have demonstrated that for certain values of effective permittivity and permeability only the backward-propagating mode can be excited by the electron beam. At the conference we will present some newly developed metamaterial designs, which we plan to employ for producing the proper effective medium parameters for this experiment.

I. INTRODUCTION AND BACKGROUND

L EFT-HANDED materials (LHMs) are artificially-created medias with simultaneously negative permittivities and permeabilities [2]. Many new electromagnetic phenomena theoretically predicted in LHMs have now found experimental verification. Those include the most basic properties, such as the negative index of refraction and negative phase velocity, and more advanced experiments, demonstrating sub-wavelength "perfect lens" imaging. However, the effect of the reverse Cherenkov radiation, although the fundamental effect of the beam-to-wave interaction, has never been experimentally demonstrated. In contrast to the well known Cherenkov effect in mediums with positive refractive index, in LHMs, due to the phase and group velocity being counter-directed, a charged particle moving with a speed greater than the phase velocity of the waves radiates energy in backward direction. LHMs exhibit negative index of refraction only near certain resonant frequencies, therefore the RCR effect in metamaterials is a resonant phenomenon and it might be used for precise beam and particle diagnostics applications.

There are at least three challenges to be overcome on the way to demonstrate RCR effect in LHMs [3]. First, the electron beam must couple strongly to the reverse wave and not radiate into other modes. Second, highly-accurate numerical methods and fabrication techniques ought to be used for the metamaterial medium to achieve proper simultaneously negative components of permittivity and permeability tensors. And third challenge is outcoupling of the radiation towards the detector with low reflection, in particular through the interface of the metamaterial and vacuum.

II. RESULTS

The proposed experimental configuration employs the localized fundamental TM mode of a circular metamaterial-loaded waveguide with a hole in the center to pass an electron beam (Fig. 1a). In this geometry only three effective medium parameters ϵ_r , ϵ_z , μ_ϕ enter the dispersion relation. In a particular imaginary case, when all of them are constant and $\epsilon_r = \mu_\phi = -0.5$, $\epsilon_z = -0.2$, the dispersion possesses a branch with a negative group velocity (Fig. 1b), which can interact with our 120 keV electron beam. Moreover the relationship $\epsilon_r = \mu_\phi$ eases outcoupling from the metamaterial to vacuum.

Fig. 1. The schematic of an LHM-loaded waveguide (a), the dispersion of electromagnetic waves inside an LHM-loaded waveguide for the case $\epsilon_r = \mu_\phi = -0.5$, $\epsilon_z = -0.2$ (black lines). Straight blue line corresponds to the dispersion of a 120 keV electron beam. (b).

There are three primary ways of realizing the above ideal geometry in practice. One of them is to use a set of co-axial disks, that is easy from a mechanical point of view, but very

complicated from the point of view of producing proper electromagnetic response, in particular, for the longitudinal component of permittivity.

Our current proposal is to construct the effective LHM cylinder by mounting a number of radial plates with metamaterial resonators etched on them. Each plate will produce negative magnetic response for the transverse magnetic field and negative electric response to any parallel electric field. It is evident that radially mounted plates with a homogeneous distribution of identical resonant structures will produce a non-homogeneous distribution of the effective medium parameters. In order to compensate for the space inhomogeneity of the resultant effective medium parameters at the selected frequency we plan to vary radially the parameters of metamaterial elements rather than their density, as the latter, due to the change of the positions of elementary resonators, can induce strong parasitic electro-magnetic coupling. As an example, Fig. 2 demonstrates the relationship between the density of plates and the split ring resonator (SRR) size which conserves the value of permeability equal to (-0.5) at a frequency of 95 GHz. The increase in the absolute value of permeability caused by the increase in the distance between SRRs is compensated here by the proper increase of the width of the ring. As the change in the properties of metamaterial cells causes the change in its dispersion, the dispersion will vary with the distance from the waveguide axis, but we expect that this effect will not negatively affect our ability to observe the RCR.

Fig. 2. SRR (a). The dependence of the SRR width, L , on the distance between SRRs in ϕ -direction, a_ϕ , which provides the constant value of $\text{Re}(\mu_\phi) = -0.5$. Here $a_\phi = a_0$ corresponds to equal spacing between centers of SRRs in all

three main directions; $L_0/a_0 = 0.72$.

To produce a negative value of permittivity, electric structures are also to be employed. The use of a metallic grid leads to a large negative epsilon region at low frequencies which results in some non-magnetic modes with a negative dispersion interacting with the electron beam [3]. It makes the use of electric resonators more preferable. However, if the electric resonator is etched in the plane parallel to SRRs then it also possesses a magnetic response, as the magnetic field is transverse to it. In this case, corresponding responses of electric and magnetic elements are not additive and the metamaterial structure should be considered for simulations as consisting of two elements from the very beginning. The required double negative electromagnetic characteristic can be achieved by employing the metamaterial resonators with both electric and magnetic responses shown in Fig. 3a. The corresponding refractive index is negative in some frequency range (Fig. 3b).

The third practical realization of the metamaterial waveguide, which is still under consideration is a set of coaxial cylinders. However, it is harder to realize from the manufacturing point of view because a negative radial electric response is needed. Developing a non-planar metamaterial manufacturing technique may be required.

Fig. 3. Elementary metamaterial cell consisting of two mirror-symmetric metallic resonators, each etched on different side of a dielectric substrate for a stronger response (a). The refractive index as a function of frequency in a loss-free approximation for the configuration shown in Fig. 3a (b).

In order to be able to operate in vacuum the system must have a low saturation vapor pressure. For this reason we propose etching the copper metamaterial elements on Kapton or other polyimide plates, which are high or even ultra-high vacuum compatible.

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