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

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***Abstract*—We have proposed an experiment on verification of the Reverse Cherenkov Radiation effect in a Left-Handed-Material-loaded waveguide. Applications of reverse Cherenkov radiation effect may range from novel higher-order-mode absorbers in microwave and millimeter-wave sources to improved particle detectors for satellite non-proliferation missions. The experimental configuration employs 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 exited by the electron beam. In this presentation we will discuss the results of simulations and different manufacturing and assembling techniques for the metamaterial-loaded waveguide.**

I. Introduction And Background

LEFT-HANDED materials are artificially-created medias with simultaneously negative permittivities and permeabilities [1]. Many new electromagnetic phenomena theoretically predicted in left-handed materials (LHMs) have now found an 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 (RCR) (Fig. 1), 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 values of the 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 backward.

There are at least three challenges to be overcome on the way to demonstrate the RCR effect in LHMs [2]. First, the electron beam must couple strongly to the reverse wave and not radiate into other modes. Second, highly-accurate techniques ought to be used for fabrication of the metamaterial medium to achieve the proper configuration with simultaneously negative several components of permittivity and permeability tensors. Finally, a concept must be developed for the outcoupling of the RCR radiation towards the detector with low reflection, in particular through the interface of the metamaterial and vacuum.

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 diagnostics and particle detection applications.

II. Results

The proposed experimental configuration employs the localized fundamental TM mode of an axisymmetrical cylindrical metamaterial-loaded waveguide with a circular hole in the center to pass an electron beam (Fig. 2a). In this geometry, the field is axisymmetric and 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 $\varepsilon_r = \mu_\varphi = -0.5$, $\varepsilon_z = -0.2$, the dispersion possesses a branch with a negative group velocity (Fig. 2b), which can interact with our 120 keV electron beam. Moreover the relationship $\varepsilon_r = \mu_\varphi$ ensures that the metamaterial has the same wave impedance as vacuum, so there is no reflection from the interface.

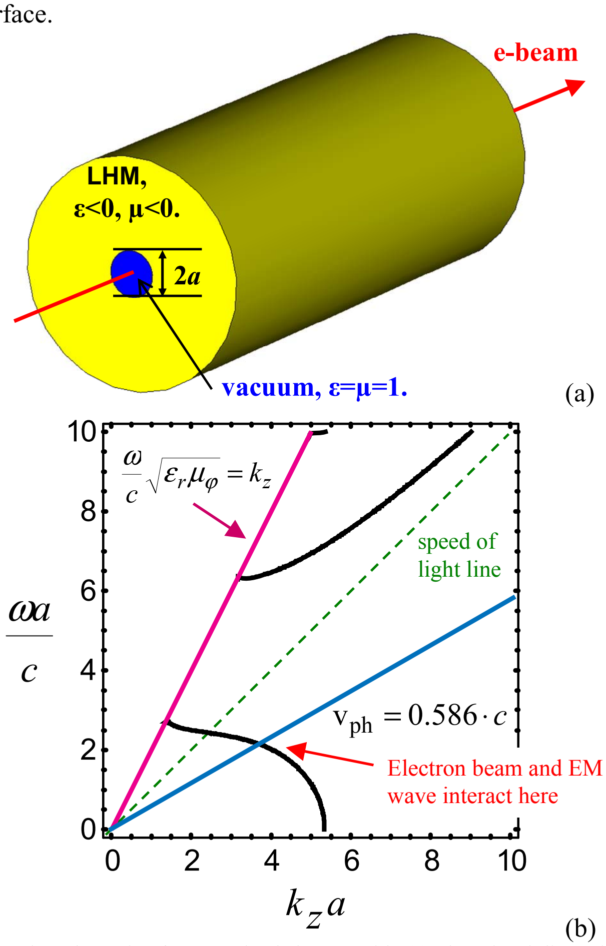

Fig. 2. The schematic of a LHM-loaded waveguide (a), the related dispersion of electromagnetic waves for the case $\varepsilon_r = \mu_\varphi = -0.5$, $\varepsilon_z = -0.2$ (black lines). Straight blue line corresponds to the dispersion of a 120 keV electron beam. (b).

This ideal design however is impossible to realize in practice. In this presentation we will discuss a couple of real-life designs and difficulties on the way of their realization.

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First of all, due to the high dispersion properties of metamaterials, one can only try to achieve specified negative parameters of the permittivity and permeability at the frequency corresponding to the beam-to-wave interaction and obtain a negative wave dispersion at this point without encountering big ohmic losses. For achieving both the negative permeability and permittivity usually a combination of split ring resonators (SRRs) (Fig. 3a) and metallic rods (Fig. 3b) or resonators with an electric response (Fig. 3c) is employed [3, 4].

To produce the magnetic response, SRRs should be oriented perpendicular to the magnetic field, which has only φ-component in our case. It means that the electric field is in the plane of SRRs, but has both the E_r and the E_z components in this plane. Each split ring represents a highly anisotropic structure, so that if the incident electric field is parallel to the split gap (i.e. $E_z \neq 0$ in Fig. 3a), then it also exhibits resonant electric and, due to the lack of mirror symmetry, coupled magneto-electric responses at the same frequency. It is possible to minimize both of these effects following the algorithm of the mutual orientation of SRRs described in [3].

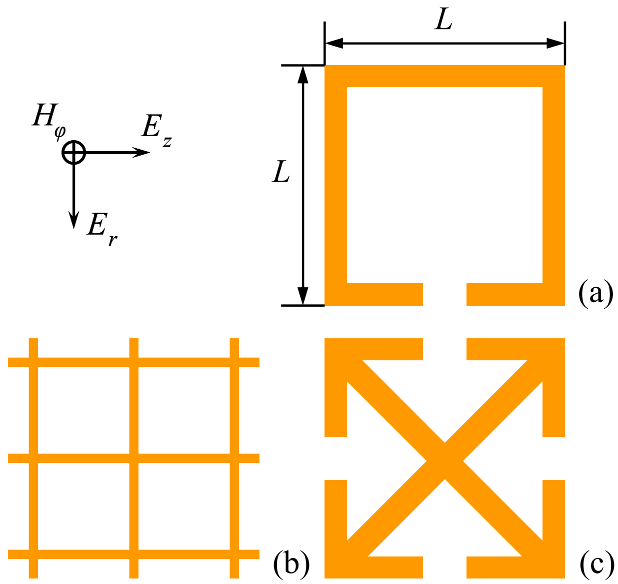

Fig. 3. Metamaterial elements with magnetic response (a) and electric response (b) and (c).

To produce a negative value of permittivity, the electric field of an incident wave should be in the plane of the structures shown in Fig. 3b and 3c. The use of a metallic grid (Fig. 3b) 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 [2], that makes the employment of electric resonators (Fig. 3c) more preferable. The problem is that 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 (Fig. 3c). 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.

In our main design, the structure is formed by radially mounted plates with metamaterial elements etched on them: magnetic elements on one side and electric on the other side. 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 SRRs, can cause bigger parasitic electro-magnetic coupling. As an example, Fig. 4 demonstrates the relationship between the density of plates and the magnetic element 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 in our case will vary with the distance from the waveguide axis, but hopefully this effect will not negatively affect our ability to observe the RCR.

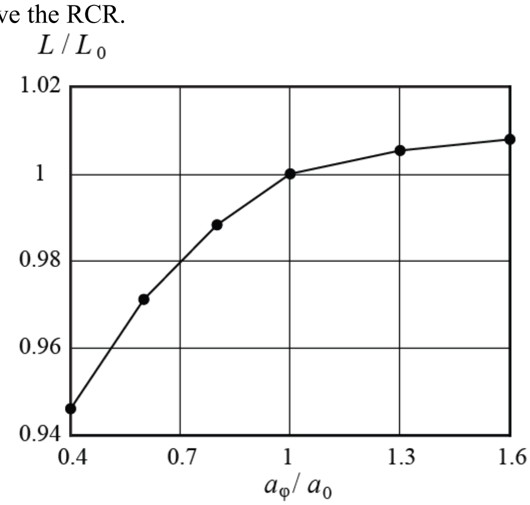

Fig. 4. The dependence of the SRR width, L (Fig. 3a), on the distance between SRRs in φ-direction, a_φ, which provides the constant value of $\mathrm{Re}(\mu_\varphi) = -0.5$. Here $a_\varphi = a_0$ corresponds to equal spacing between centers of SRRs in all three main directions; $L_0/a_0 = 0.72$.

We also considered an alternative geometry for the metamaterial structure, although somewhat harder from the manufacturing and the alignment points of view. It employs a set of coaxial cylinders. The main difficulty here is to realize a negative radial electric response. Developing the non-planar metamaterial manufacturing technique may be required.

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 plates.

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