Observation of Wakefield Generation in Left-Handed Band of Metamaterial-Loaded Waveguide

Sergey P. Antipov[1]***, Linda Spentzouris***[2]***, Wei Gai***[1]***, Wanming Liu***[1] ***and John G. Power***[1]

[1]Argonne National Laboratory, 9700 S. Cass ave, Argonne, IL, United States (antipov@anl.gov)

[2]Illinois Institute of Technology, 3300 South Federal Street, Chicago, IL

Abstract

We report a design of a TM-mode based metamaterial-loaded waveguide. Network analyzer measurements demonstrated a left-handed propagation region for the TM_{11} mode at around 10 GHz. A beamline experiment was performed with the metamaterial-loaded waveguide. In this experiment, a 6 MeV electron beam passes through the waveguide and generates a wakefield, via the Cherenkov radiation mechanism. We detected a signal in the left-handed frequency band at 10 GHz. This is an indirect demonstration of reverse Cherenkov radiation as predicted in theory. Cherenkov radiation in artificially constructed materials (metamaterials) can be advantageous for particle detector design.

1. Introduction

The electromagnetic properties of a medium in most cases are characterized by the permittivity ε (response to electric field) and the permeability μ (response to magnetic field). Typically ε and μ are positive or tensors with positive values for most frequencies of electromagnetic waves. In this case, the phase vector (k) of the wave propagating through the medium forms a right-handed system with the field vectors E and B. The Poynting vector is co-directed with k.

Veselago first pointed out that propagation is also possible when ε and μ are simultaneously negative [1]. Propagating waves in such double-negative media (DNM) exhibit several unusual properties. First of all, the phase vector forms a left-handed system with the field vectors. This is why materials with simultaneously negative ε and μ are called left-handed (LHM). In such media the Poynting vector, which is collinear with the group velocity, is counter-directed to the phase vector. This gives rise to several unusual effects like the reversed Doppler Effect, reversed Cherenkov radiation (CR) [1, 2, 3 and 4] and negative refraction [1].

Materials (metamaterials, MTM) with simultaneously negative values for ε and μ were artificially constructed in 2000 [8]. The arrays of sub-wavelength elements respond to electromagnetic fields like a medium with dispersive (frequency dependent) permittivity and permeability. Split ring resonators (SRR) [6] create an effective magnetic material with μ negative at certain frequencies. Artificial ε can be produced for example by wire arrays [7]. It is possible to create a metamaterial with simultaneously negative ε and μ [8].

Characteristics analogous to reverse Cherenkov radiation were demonstrated [9] by employing current pulses in microwave radiating systems. However, there have been no experiments involving a beam of charged particles. We recently reported on the first beam test of a metamaterial-loaded waveguide [16]. The source used was the 6 MeV electron beam produced by the Argonne Wakefield Accelerator (AWA) photoinjector.

Cherenkov radiation is widely used in accelerator physics for beam and particle detector applications. Reverse Cherenkov radiation, predicted for double-negative materials, can have unique features useful for beam detection [2, 3, 4, 15]. Metamaterials can be used as an engineered medium for detectors designed to produce radiation that counter-propagates with respect to the particle beam source within a selected frequency band. Originally metamaterials were produced for microwave frequencies using printed circuit board techniques. During the past 7 years metamaterials were realized in the THz range and up to optical frequencies [see, for example, 10 and review 11]. Optical metamaterials would be perfect for Cherenkov detectors, which operate generally in the optical region. To understand the physics of the process we worked with microwave metamaterials because they are easier to manufacture.

We have designed and manufactured a double-negative metamaterial similar to those developed by other groups. In [12, 13] we reported our first metamaterial design and in [14] reviewed our plans for accelerator – related metamaterial research. We observed much better transmission level and stability to manufacturing tolerances for a loaded waveguide configuration than for an open structure. Thus, we are using a metamaterial-loaded waveguide configuration for our studies.

In [15] we discussed some theoretical aspects of particle interaction with a metamaterial placed in a waveguide. For the case of a loaded waveguide, Cherenkov radiation generated by charged particle propagation through the structure is usually called a wakefield, in analogy to the wake generated behind a boat on a river. We developed a simulation approach to determine the frequency and the level of excitation of waveguide modes from a charged particle beam. Interesting properties of Cherenkov radiation in a dispersive and anisotropic medium can be utilized for particle detection [2, 3 and 15].

Here we will review the design and implementation of the TM mode based metamaterial-loaded waveguide [16]. Cold tests of the MTM-loaded waveguide demonstrated a left-handed band at 10 GHz frequency. We then review our first beam test of the waveguide [16]. In this experiment a 6 MeV, ¼ nC electron beam passed through the metamaterial-loaded waveguide. We determined that a 10 GHz component was excited in the wakefield spectrum. This is an indirect demonstration of wakefield generation in a left-handed band. The frequency response of the beam data matched the left-handed frequency band demonstrated in the cold test, but explicit verification of the direction of propagation has not yet been done. Direct demonstration could be performed with a multi–probe measurement or the employment of a directional coupler. For this first experiment, loose manufacturing tolerances and probe calibration issues prevented us from making a decisive statement that the radiation was backward. However, the beam data are entirely consistent with both simulation results and cold test measurements.

2. Design of the metamaterial - loaded waveguide

For the metamaterial design we picked a typical split ring resonator and wire array configuration. We have SRRs and wires arranged in a 2-D grid (see Fig. 1). This way we have metamaterial elements aligned along both x and y directions. This is done to match TM_{11} mode field patterns. We will assume a waveguide to be aligned longitudinally with the z-axis. The effective tensors for permeability and permittivity are:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix} \qquad \varepsilon_\perp = 1 + \frac{\omega_{pe}^2}{\omega_{re}^2 - 2i\omega_{de}\omega - \omega^2} \qquad \varepsilon_\parallel = 1 \tag{1}$$

$$\hat{\mu} = \begin{pmatrix} \mu_\perp & 0 & 0 \\ 0 & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix} \qquad \mu_\perp = 1 + \frac{F\,\omega^2}{\omega_{rm}^2 - 2i\omega_{dm}\omega - \omega^2} \qquad \mu_\parallel = 1 \tag{2}$$

Dispersion parameters are controlled through the element geometry [6, 7]. The design values are incredibly sensitive to the manufacturing tolerances. Some theoretical and practical details are discussed in [16].

The split rings were designed to have a resonance at around 9.5 GHz. They were produced by conventional printed circuit board technology (PCB). Then they were assembled into a beehive (cell) structure. Wires, made of 1 mm thick magnet wire, penetrate the split rings. The waveguide was chosen to be square (1.34 X 1.34 inch, cutoff frequency ~6.2GHz), rather than rectangular, to maintain a TM_{11} mode symmetry closer to that of a circular waveguide. It was manufactured having small grooves (see Fig. 1) to hold the metamaterial PCB boards. For the TM_{11} mode such grooves are not destructive, since the surface currents are longitudinal.

3. Bench measurements of the TM_{11} mode propagation through metamaterial-loaded waveguide

For cold tests we used a standard HP8510C network analyzer. The source from the network analyzer is an electromagnetic pulse that is transformed to a particular mode or modes of the structure under test. This transformation is done by a mode launcher. We had to design and custom make the TM_{11} mode launcher. More details on the design are in [16].

In the cold test we were able to identify the left-handed region for the combined structure. In this region, there is a resonant transmission drop for the SRR-only structure. The wire array exhibits plasma like behavior, suppressing transmission over a broader range of frequencies, except with a resonant transmission peak due to additional capacitance between the waveguide wall and tips of the wires. The combined structure shows transmission in the region near 10 GHz (see Fig. 1), where neither the SRR-structure ($\mu < 0$) nor the wire array ($\varepsilon < 0$) have transmission. To our knowledge, this is the first left-handed metamaterial – based TM_{11} mode waveguide designed and experimentally tested.

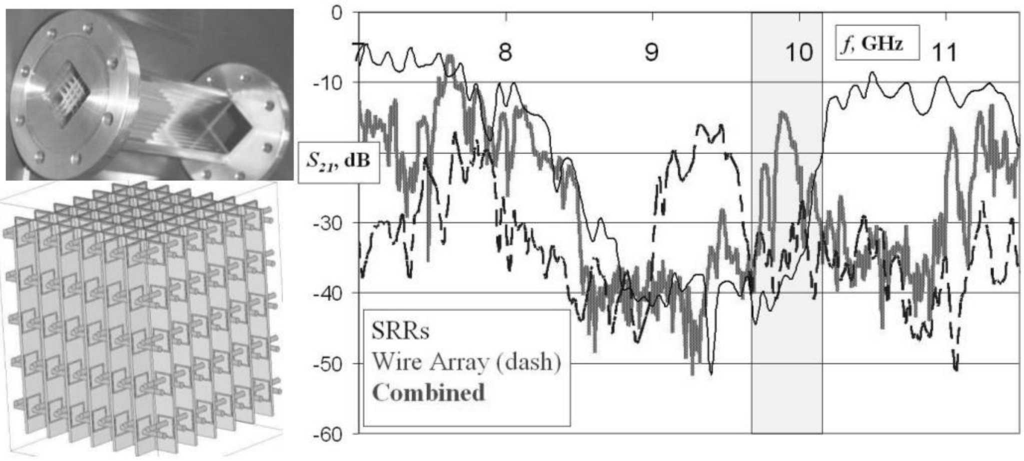

Figure 1. Left: metamaterial design. Waveguide with metamaterial inside (two walls removed). Right: Combined bench measurement data. Transmission of the TM_{11} mode through the waveguide loaded with SRRs (thin solid line), through the wire array (thin dashed line) and through the combined structure (wire array + SRRs) (thick line). The combined structure has a transmission peak in the region 9.7-10.2 GHz, where neither SRRs nor wires exhibited transmission. This is the signature of left-handed band.

4. Measurement of wakefield generated by an electron beam passing through the metamaterial – loaded waveguide

We had a 0.25 nC, 3 mm (10 ps) longitudinal size beam passing through the metamaterial waveguide. The generated signal was picked up by side wall probes. It had to be attenuated before reading it with an oscilloscope. On the oscilloscope we observed time resolved voltage signals (wakefield) from the waveguide side wall probes.

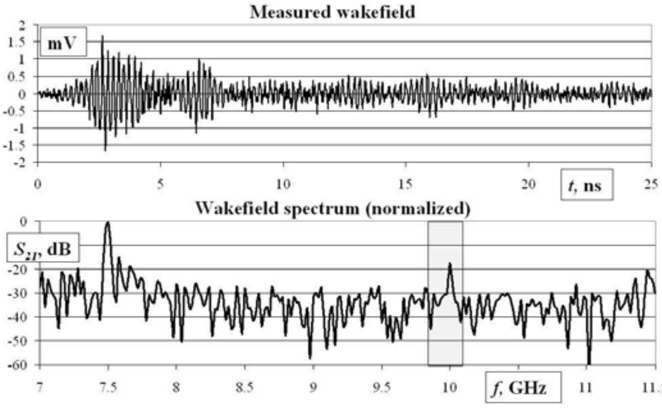

Figure 2. Results of the beam test: single voltage probe measurement. The top portion of the figure shows the time dependent amplitude of the wakefield measured upon passage of the electron bunch. The bottom shows the normalized frequency spectrum of the wakefield. We observe that the wakefield has a measurable 10 GHz peak above the noise floor. This corresponds to response of the structure in the left-handed band.

We performed a Fourier transform of the signal to obtain spectral data, and then compare it to data from the cold test. It can be clearly seen, that there is a wakefield excitation at around 10 GHz (see Fig. 2). As we demonstrated previously with the network analyzer (cold) test, the 10 GHz region is the double-negative region (see Fig. 6). Therefore, this measurement is the first indirect demonstration of reversed Cherenkov radiation in a quasi-continuous medium (a metamaterial, as opposed to corrugated waveguides used in backward wave oscillators). To demonstrate the backward mode directly, we have to perform a measurement with multiple probes. This measurement requires precise calibration of probes. While we did perform multiple probe measurements, manufacturing tolerances, probe and cable calibration requirements, and beam fluctuations made it practically impossible to make a decisive statement as to whether we observe a backward mode directly or not.

5. Conclusion

Metamaterial – loaded waveguides have potential applications as higher order mode absorbers and beam position monitors. Theoretically the reverse Cherenkov effect in left-handed metamaterials has interesting properties for particle detection. The strength of artificially constructed double-negative metamaterials is that they may be customized to exhibit a unique electromagnetic response not available in natural materials. In this paper we presented experimental results of a charged particle beam interaction with double-negative metamaterial structure.

Our previous theoretical and simulation work [15] on double-negative metamaterial loaded waveguides has now been followed up with experimental measurements. We designed a 2D metamaterial for a TM mode based waveguide. We performed cold tests with a network analyzer and demonstrated a left-handed band for the TM_{11} mode at around 10 GHz frequency. These were followed up with particle beam tests that showed generation of a strong signal in left-handed band at 10 GHz [16]. This is an indirect demonstration of wakefield generation in left-handed band. To demonstrate the backward radiation directly some modifications of the design are needed to address issues of manufacturing tolerances and filtering of frequency content imposed by probes and cables.

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