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EXPERIMENTAL DEMONSTRATION OF DOUBLE-NEGATIVE METAMATERIALS PARTIALLY FILLED IN A CIRCULAR WAVEGUIDE

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Abstract—We have studied a new type of double-negative metamaterials (DNMs) composed of split ring resonators (SRRs) and wire strips with substrate teflon, suitable for generation of reversed Cherenkov radiation (RCR) which is TM radiation. We have experimentally observed a narrow pass band in a circular waveguide partially loaded with the DNMs and stop bands for SRRs-only with teflon and for wire strips-only with teflon, respectively. The experimental data show that the DNMs exhibit double-negative behavior over a frequency band of interest. This study provides a foundation for future experiment to observe RCR emitted by charged particles.

1. INTRODUCTION

In the past ten years, there has been a renewed interest in developing composite materials. The artificial materials with simultaneous, effective negative real permittivity and permeability, exhibit exotic electromagnetic properties such as negative index of refraction [1–3], reversed Doppler shift [4], and reversed Cherenkov radiation (RCR) [5–11] which was considered for the first time by Pafomov [12]. *Slab* metamaterials have been demonstrated by many experiments (for examples in [13, 14]) for many potential applications in components, devices, antennas, and superlens, etc., operating at microwave and optical frequencies [15–25].

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RCR is well known from backward wave oscillators (BWOs) using slow-wave structures like wire helix or coupled cavities for high power. For double-negative metamaterials (DNMs), there is an enhanced electromagnetic radiation compared to the existing slow-wave structures [26]. Another advantage of employing the new artificial structure presented here is that its effective permittivity and permeability can be manipulated by precisely controlling the composite structure's geometry and its size and then steering the phase velocity of the propagating electromagnetic wave. RCR has potential applications in particle detection, electromagnetic wave production at microwave and optical frequencies, material characterization, and so on [8].

At present, RCR emitted by charged particles in double-negative metamaterials (DNMs) has not been directly observed, because there are many challenges in experiment, especially in fabricating DNM worked in vacuum. In this paper, we propose a new DNM which consists of split ring resonators (SRRs) exhibiting negative real permeability and two orthogonal wire strips exhibiting two negative real permittivities. Thus, a circular waveguide partially loaded with the DNM was experimentally studied in details in order to demonstrate the double-negative behavior for the proposed metamaterials. The experimental data provided here show that this cylindrical shaped DNM exhibits double-negative nature over a usable frequency band and is thus suitable to be used for beam tests. It is a necessary step for our next experiment to observe RCR using charged particles. We plan to use this DNM structure in a beam test to experimentally observe RCR.

2. EXPERIMENTAL STUDY AND DISCUSSION

We followed the common design method [27–29] to obtain a structured DNM suitable for TM waves. The DNM samples employed in our experiment were mostly fabricated as periodic structures, the unit cell of which consists of a copper SRR etched on one face of the 0.25 mm thick teflon substrate and two orthogonal wire strips mounted on its opposite face. The SRRs are periodically arranged in the azimuthal direction and the wire strips with the same width t as the SRRs are also periodically positioned in the radial and the axial directions, respectively, as shown in Figure 1(a).

We design three layers in the radial direction with the lattice constants in the radial, azimuthal, and axial directions ($a_r = 3.3\,\mathrm{mm}$, $a_\theta = 5\,\mathrm{mm}$, $a_z = 5\,\mathrm{mm}$) to keep the density of the unit cell in the azimuthal direction constant. Therefore, there are 6, 10, and 14 unit cells in the azimuthal direction for the first, the second and the

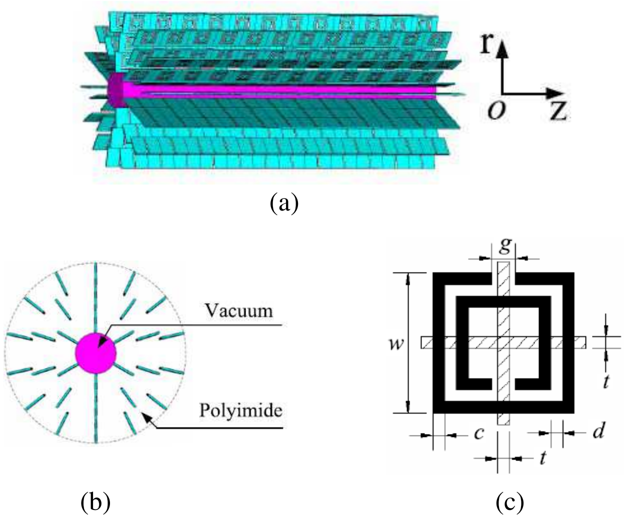
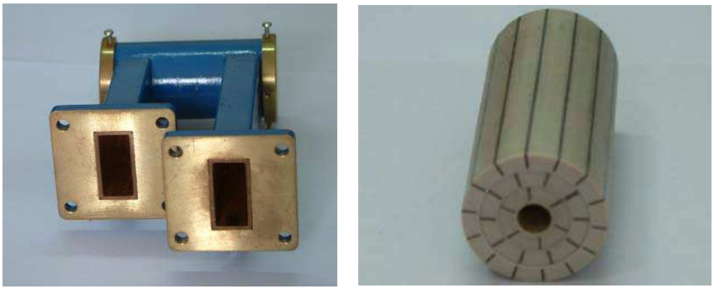


Figure 1. (a) Scheme of the DNMs suitable for RCR; (b) Cross-section scheme of the DNMs; (c) Schematic drawing of a unit cell. The square SRR (black) and the wire strips (dashed) have the following parameters: $c = 0.2\,\text{mm}$, $d = 0.15\,\text{mm}$, $g = 0.3\,\text{mm}$, $w = 2.2\,\text{mm}$, $t = 0.14\,\text{mm}$, and the thickness of all the copper employed here is $17\,\mu\text{m}$.

third radial layers, respectively, as illustrated in Figure 1(b). For the axial direction, there are 12 unit cells with a total axial length of the engineered DNMs being 60 mm. The teflon printed circuit boards (PCBs) with unit cells were cut and carefully assembled into the slots of the annular polyimide material with a 3 mm radius hole at the center of the cylinder designed for an electron beam to go through (Figures 1(a), (b)), with one unit cell of the DNMs shown in Figure 1(c). The supporting dielectric material was chosen so that the entire apparatus can operate in vacuum [30]. Finally, the polyimide material with the assembled PCBs was precisely inserted into the circular waveguide, as shown in Figure 2(a). The wire strips and the SRRs would produce the dielectric-like and magnetic material-like responses, respectively, and the structured metamaterials exhibit simultaneously negative real permittivity and permeability in a frequency band of interest.

Why did we make the DNMs with the SRRs in the azimuthal direction and wire strips in the radial and axial directions? It is because Cherenkov radiation is a TM radiation, which requires the DNMs with at least two negative real permittivities and one negative



(a) (b)

Figure 2. Prototype of (a) the mode converter and (b) the annular polyimide with PCBs, respectively.

real permeability. For a dominant mode TM or quasi-TM in the circular waveguide partially loaded by the DNMs, the DNMs must exhibit negative real permittivities in the radial and the axial directions and negative real permeability in the azimuthal direction [30–33]. Therefore, the DNM-loaded waveguide like a slow-wave structure can propagate the slow-wave.

In order to perform the transmission and reflection measurements in a waveguide environment, the experimental setup consists of a HP8719C network analyzer and the mode converter (Figure 2(a)) where the circular waveguide is partially loaded with the annular polyimide inserted with PCBs (Figure 2(b)). We first manufactured and tested the SRRs-only structure. The scattering parameter S_{21} is shown in Figure 3. Meanwhile, in order to judge the negative permeability region, we also manufactured and tested the closed-SRRs-only structure [34]. The splits in the SRR structure play a key role in obtaining magnetic resonance. Removing the splits prevents the current from flowing between the inner and outer rings, and therefore, the magnetic resonance is no longer present. In the experiment, we can determine that the electromagnetic wave can not propagate when the amplitude of S_{21} is below $\sim -20\,\text{dB}$, and thus the negative real permeability should be in the frequency region $\sim 8.9 - \sim 11.4\,\text{GHz}$ as compared with the closed-SRRs-only case, as shown in Figure 3.

For comparison, we then manufactured and tested three types of strips-only with teflon structures respectively: strips-only along the radial direction, strips-only along the axial direction, and their combined structure. Also, we measured the transmission property for the strips-only with teflon structures with all other parameters held as close to the original DNMs as possible. The periodic arrangement of thin wire strips was previously shown to have plasma frequencies

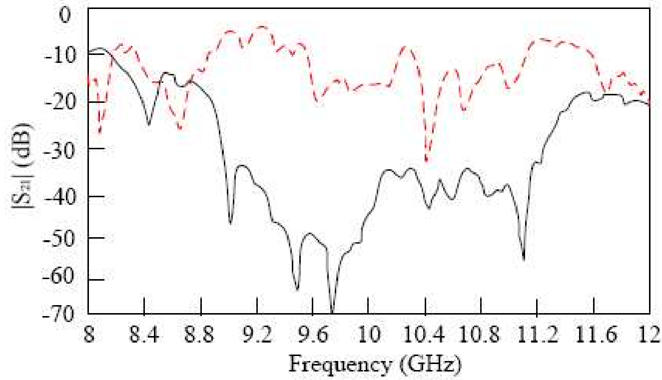


Figure 3. Experimental transmission data for the SRRs-only (solid line) and the closed-SRRs-only (dashed line) with teflon cases.

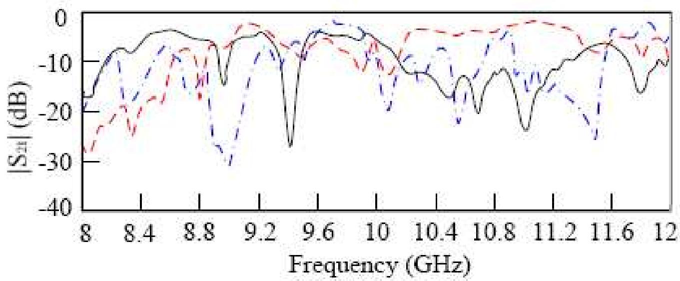


Figure 4. Experimental transmission data for the wire strips-only along the radial (dash-dot line) and axial (dashed line) directions respectively and both strips (solid line) cases.

at microwave frequencies [2]. The measured data for the three cases are shown in Figure 4. The wire strips-only along the radial and axial directions does not propagate electromagnetic waves around ~ 9.0 GHz and around ~ 8.3 GHz, respectively, while the combined structure does not propagate electromagnetic waves around ~ 9.3 GHz. Obviously, there is a cross-talk when both strips are present. This fact can be explained by the negative effective real permittivity [2].

At last, we manufactured and tested the DNM structure, which is shown in Figure 2(b). The measured results of S_{21} are plotted in Figure 5. In order to further judge the double-negative region, we also measured the "without PCBs" case, also plotted in Figure for comparison. When the amplitude of S_{21} for the DNM case is

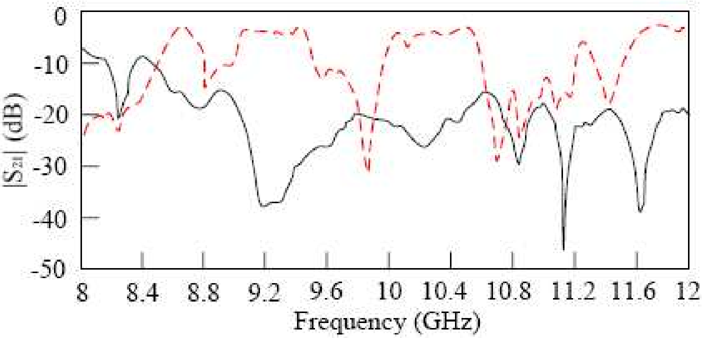


Figure 5. Experimental transmission data for the DNMs (solid line) and the "without PCBs" (dashed line) cases.

greater than $\sim -20\,\mathrm{dB}$, we think that the electromagnetic wave can propagate in this structure, and simultaneously consider the negative real permittivity or permeability region and the "without PCBs" case as well, we can determine that the double-negative nature should appear in the frequency region ~ 8.4 to $\sim 8.8\,\mathrm{GHz}$.

By comparing these cases mentioned above with the "without PCBs" case, we conclude that the dips around ~ 9.9 and $\sim 10.7\,\mathrm{GHz}$ in the transmission spectra do not originate from the SRRs or wire strips but from the large intrinsic reflection of the system at these frequencies. Therefore, the TM can be propagated from ~ 8.4 to $\sim 8.8\,\mathrm{GHz}$, in other words, the proposed metamaterials exhibit the double-negative behavior at these frequencies. Note that Figure 5 clearly shows that the DNM loss is larger than that of the normal material without PCBs.

We should mention that there is a distinct frequency shift phenomenon. Similar phenomena were observed in the experiments for the *slab* case [35]. The shift presented here can be qualitatively explained by the equivalent circuit model as follows: in the presence of teflon and wire strips, there is an additional inductance due to wire strips relative to the SRRs-only with teflon case and there are mutual capacitance and mutual inductance because of the coupling between the SRRs and wire strips.

The retrieval of material parameters for the DNMs loaded within a waveguide is rather complicated, because of the field distribution. In a non-coaxial guide, such as a rectangular or circular waveguide, the TEM is not supported so that there are field components in the direction of propagation. If the DNMs are not isotropic, then the retrieval of parameters from the measurements of the scattering parameters becomes more complicated, as the waveguide dispersion plus the anisotropy of the medium need to be included. As we know, a retrieval approach for a material within a waveguide has not been published in the literatures. Therefore, we will make effort to solve this problem in the future.

3. CONCLUSION

In conclusion, we have designed and manufactured a new type of the DNM with the SRRs and wire strips. We also have experimentally verified the double-negative behavior of the proposed metamaterial partially loaded in a circular waveguide within a narrow frequency band. Certainly, the proposed DNMs can be scaled up to higher frequencies such as Terahertz frequencies for potential applications. We will use this artificial material partially loaded in a circular waveguide to directly detect RCR emitted by charged particles in the future.

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