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EXPERIMENTAL STUDY OF $\lambda/4$ MONOPOLE ANTENNAS IN A LEFT-HANDED META-MATERIAL

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Abstract—The paper focuses on $\lambda/4$ monopole antennas located in a meta-material that exhibits simultaneously negative values of effective permeability and permittivity within a microwave frequency band, as well as our experimental study in an anechoic chamber. The experimental results show that the electromagnetic waves radiated by the monopole are negatively refracted at the interface between the meta-material and the air at certain directions. In addition, the radiation pattern of the monopole in the meta-material is directional while it is non-directional without the meta-material.

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1. INTRODUCTION

In the past few years, the meta-materials with permittivity and permeability both taking real negative values have been considered in many publications. So far, there are several experiments to verify the left-handed properties of these meta-materials. In 2000, David Smith of the University of California at San Diego and his colleagues constructed the first LHM based on a periodic array of interspaced conducting nonmagnetic split-ring resonators and continuous metallic wires. [1] The negative permeability region begins at 4.2 GHz and ends at 4.6 GHz. In 2001, this group made another LHM at X-band and verified the negative index of refraction [2] predicted by Veselago. [3] In 2002, Mehmet Bayindir et al. studied the transmission properties of LHM in free space, [4] which also verified the existence of negative permeability and permittivity. Also in 2002, Stefan Enoch et al. studied the directive emission of a source embedded in a slab of meta-material. [5] In 2003, Ran Lixin, Hongsheng Chen of Zhejiang University and their colleagues made the first beam shifting experiment and T-junction waveguide experiment to verify the negative refraction [6, 7]. They also did an experiment to confirm negative refractive index of a meta-material composed of Ω-like metallic patterns. [8] We constructed a large LHM and studied the transmission properties in an anechoic chamber in 2003. [9]

In this paper, a type of meta-material composed of periodical arrangement of thin copper strips and split ring resonators (SRRs) is studied. The radiation properties of a $\lambda/4$ monopole antenna in the meta-material was measured in an anechoic chamber.

2. EXPERIMENTAL SETUP AND THE STRUCTURE OF META-MATERIAL

The meta-material was constructed as follows: the wire strips and SRRs were printed on two separate printed circuit boards by etching technique. The thickness and the relative permittivity of the boards are 0.5 mm and 2.65, respectively. The SRRs and wire strips are 0.035 mm thick. The size of the square board is $246 \times 246\,\text{mm}^2$. The width and length of the strips are 0.5mm and 238 mm respectively. There are 48 strips on one board. The distance between the strips is 5 mm. The configuration of a single SRR has a geometry which is similar to the previously reported structure. [2,4] The details of a single SRR are shown in Figure 1. It consists of two square rings separated by a gap. There are 2304(48 × 48) SRRs, which are separated by 5 mm, on one board of $246 \times 246\,\text{mm}^2$.

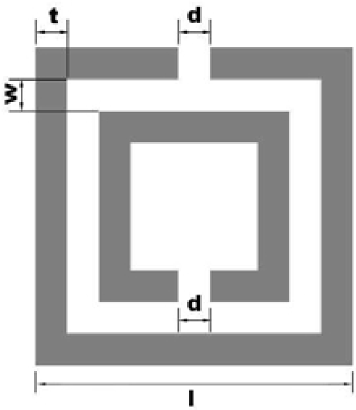

Figure 1. Single SRR with parameters $l = 3\,\text{mm}$, $d = t = w = 0.3\,\text{mm}$.

Three different media were fabricated by combining the SRR and the strip boards. The three media are as follows: Medium-1 is made by placing 50 identical SRR boards in parallel arrangement with 5 mm in distance, Medium-2 by placing 49 identical strip boards in parallel arrangement with 5 mm in distance, and Medium-3 by stacking 49 strip boards and 50 SRR boards in a periodic arrangement with 2.5 mm in distance.

The main instruments used in our experiments were an Agilent 8722ES vector network analyzer, a microwave horn antenna, and a receiving monopole with conducting ground plane. The assembled dimensions of the horn antenna are 27.9 cm in width, 15.9 cm in height, and 24.4 cm in length. The height of the receiving monopole above the conducting ground plane ($250 \times 250\text{mm}^2$) is about 7.5 mm.

As seen in Figure 2, a $\lambda/4$ monopole with ground plane was placed in the medium. The flat conducting ground plane is made of copper of $270 \times 246\,\text{mm}^2$. The horn antenna or the receiving monopole was placed beside the medium. The Agilent 8722ES was connected to the monopole in the medium and the horn antenna or the receiving monopole beside the medium via two coaxial cables. We studied the radiation characteristics of the monopole in the meta-material by measuring the scattering parameters matrix when the monopole is in Medium-1, Medium-2, Medium-3, and the Air respectively.

As seen in Figure 2, we placed a $\lambda/4$ monopole in the media. The flat conducting ground plane is made of copper of $270 \times 246\,\text{mm}^2$. The horn antenna or the receiving monopole was placed beside the media.

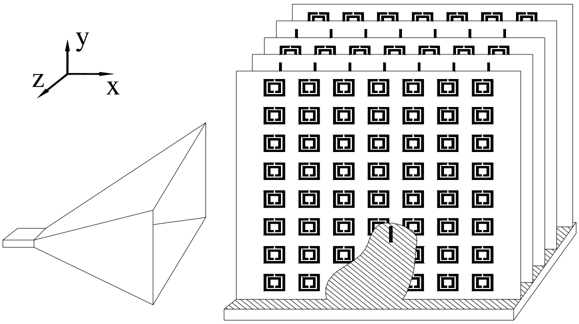

Figure 2. Experiment setup of monopole in meta-material.

3. EXPERIMENT RESULTS AND EXPLANATIONS

3.1. Measured S_{11} of Monopoles in Different Media

Figure 3 to Figure 6 shows the measured S_{11} of the monopoles of different lengths in different media. The lengths of the monopoles are about 9.3 mm, 7.5 mm, 6.2 mm, and 5.3 mm respectively.

From Figure 3 to 6, we decide to use the monopoles of $h = 7.5$ mm and $h = 6.2$ mm in our experiments.

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3.2. The Frequency Band of Negative Permeability and Permittivity

Figures 7 and 8 show the measured S_{21} when the monopoles are in different media. Each figure has four curves showing the results of the monopole ($h = 7.5$ mm) in Medium-1 (SRRs only), Medium-2 (strips only), Medium-3 (SRRs & strips), and the Air, respectively. The horn antenna was placed beside the medium. The distance between the monopole and the horn aperture is about 20 cm.

The following facts can be derived from Figures 7 and 8: When the monopole is in Medium-1, electromagnetic waves can not propagate within 10–10.5 GHz, but can propagate in the rest of the frequency band. This means that the effective permeability of Medium-1 within 10–10.5 GHz is negative. When the monopole is in Medium-2, electromagnetic waves cannot propagate in the frequency band under test, which means that the effective permittivity of Medium-2 is negative. When the monopole is in Medium-3, S_{21} at 10.3–10.8 GHz is higher than that at other frequencies. Because the meta-material consisting of 50 pieces of SRR boards and 49 pieces of strip boards is

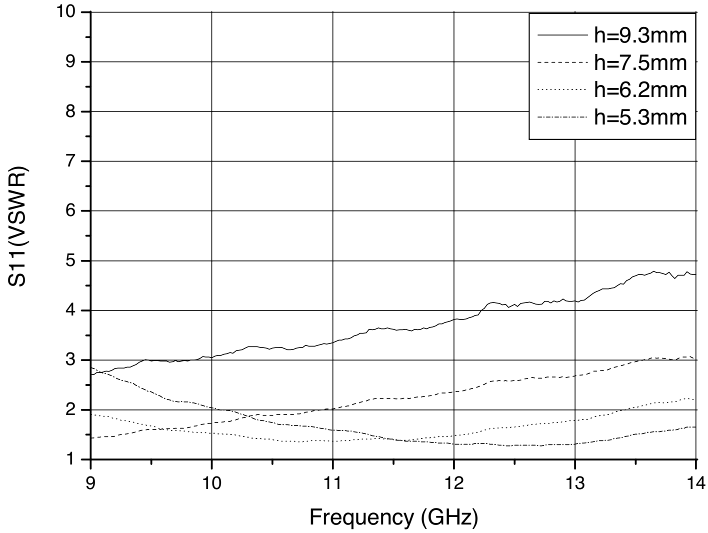

Figure 3. Measured S_{11} of monopoles of different length in the Air.

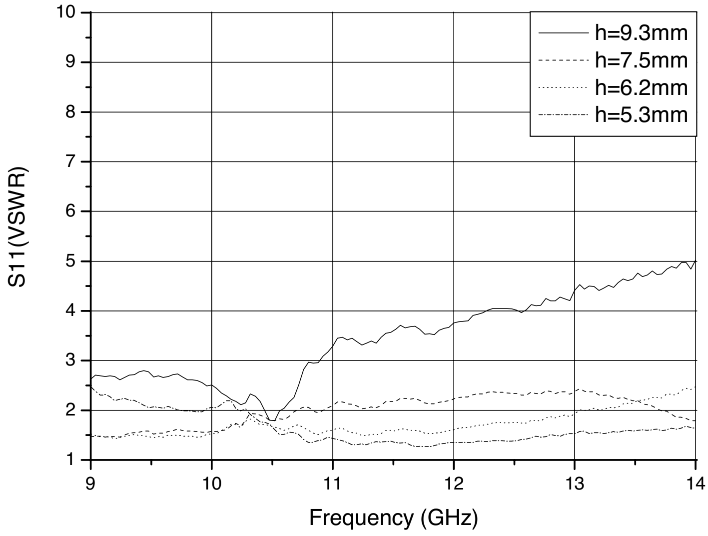

Figure 4. Measured S_{11} of monopoles of different lenth in Medium-1 (SRRs only).

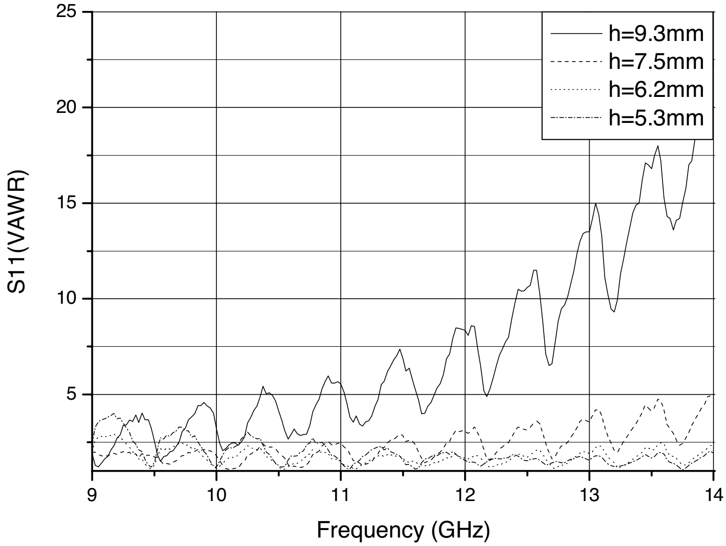

Figure 5. Measured S_{11} of monopoles of different length in Medium-2 (strips only).

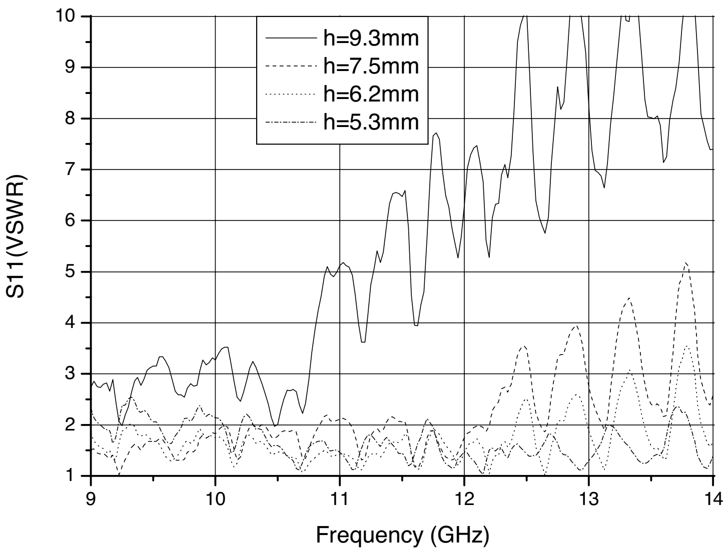

Figure 6. Measured S_{11} of monopoles of different length in Medium-3 (SRRs & strips).

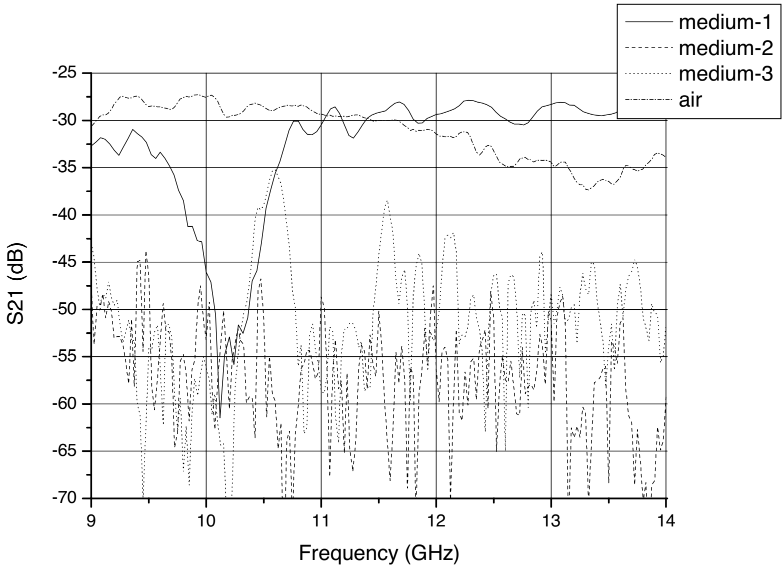

Figure 7. Measured S_{21} of $h = 7.5\,\mathrm{mm}$ monopoles in different media.

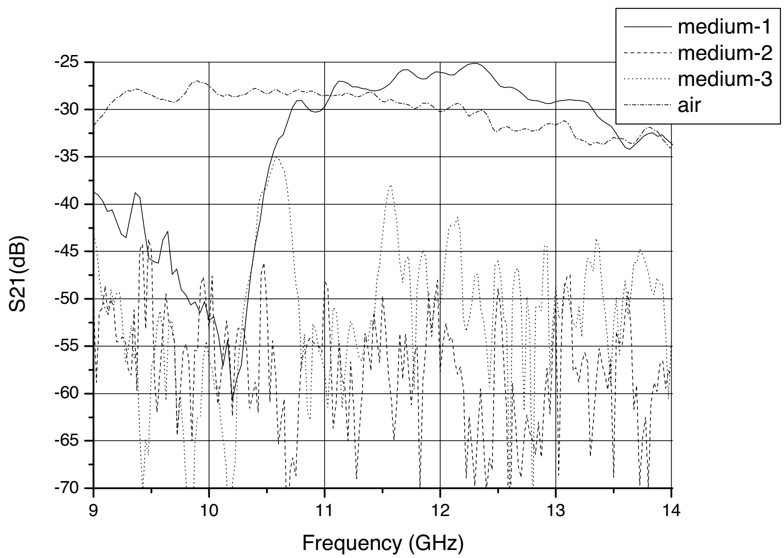

Figure 8. Measured S_{21} of $h = 6.2\,\mathrm{mm}$ monopoles in different media.

rather large, the attenuation of the waves in the meta-material would be very serious. Although S_{21} at 10.3–10.8 GHz is not much higher than that at some frequencies beyond 10.3–10.8 GHz, it is reasonable to consider electromagnetic waves can propagate along the x-axis within 10.3–10.8 GHz but cannot propagate in the rest of the frequency band, which means that both the effective permeability and the effective permittivity may be negative within 10.3–10.8 GHz. This conclusion is also supported by the following two experiments.

3.3. The Radiation Pattern in x-z Plane

The radiation pattern in x-z plane was measured by rotating the Medium-3 around the axis of the monopole.

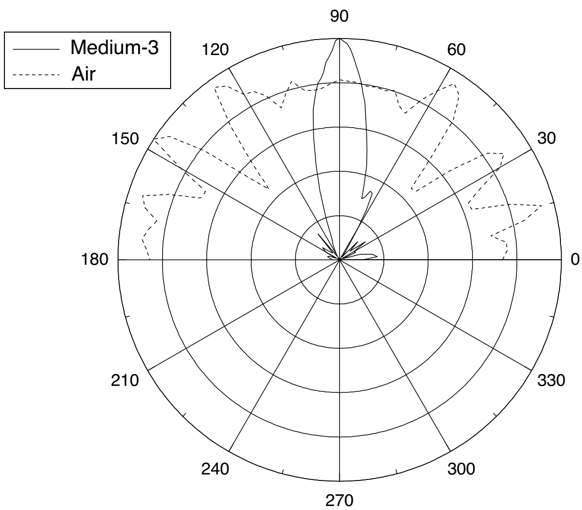

Figure 9. Normalized field pattern of 10.6 GHz.

Figure 9 shows the measured result of normalized field pattern of 10.6 GHz. The reference angle 0°. means that the normal direction of the boards is along the x-axis. The radiation pattern of the monopole in Medium-3 is directional while it is non-directional in the Air, which was also observed in [5]. The maximum radiation direction is perpendicular to the normal direction of the board. Because both the effective permeability and permittivity are negative at this direction, the waves radiated by the monopole can pass through Medium-3. When the angle changes from 0° to ±90°, the effective permeability changes to be positive gradually while the effective permittivity remains negative. The electromagnetic waves change to non-propagable gradually. It is clear that the meta-material is anisotropic.

In theory, the radiation pattern in x-z plane of monopole with large ground plane in the air should be a circle. Because the ground plane is not very large in our experiment, the measured pattern is approximately a circle and because the framework that holds the strip and SRR boards remains when we tested the monopole without the meta-material, there are pits at $45° \pm 10°$ and $135° \pm 10°$.

3.4. Verification of Negative Refraction

According to V. G. Veselago's prediction, when a beam of radiation is incident on an interface between right-handed material (RHM) and left-handed material (LHM), the refracted ray is bent on the same side of the normal as the incident ray. As shown in Figure 10, if the transmitting monopole is in the LHM, the radiation beam should bend downwards. In order to verify the negative refraction, we moved the receiving monopole antenna up and down and measured the S_{21} at different position. In our experiment, the distance between the transmitting monopole and the receiving one is about 30.5 cm.

Figure 11 shows the measured S_{21} of 10.6 GHz in the test of Figure 10. It is because both the effective permeability and permittivity of Medium-3 may be negative within 10.3–10.8 GHz that we choose the frequency of 10.6 GHz for the sake of illustration.

Figure 11 has four curves showing the S_{21} when the transmitting monopoles (h = 7.5 mm and h = 6.2 mm) are in Medium-3 and the Air, respectively.

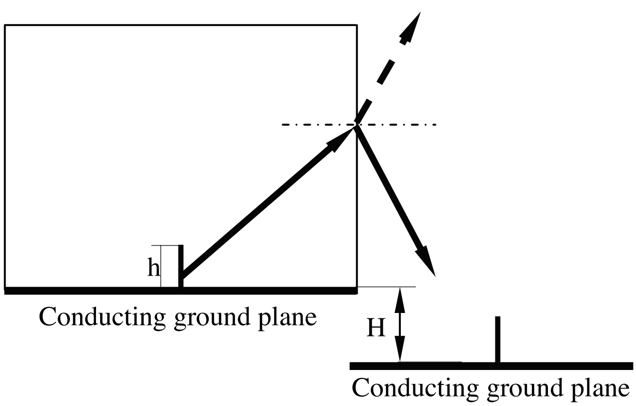

Figure 10. Experimental setup for refraction received by monopole.

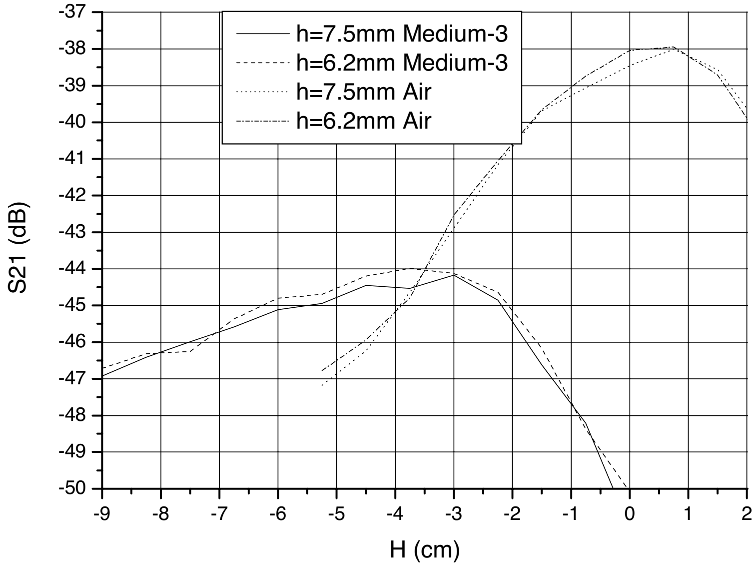

Figure 11. Measured S_{21}s received by monopole.

From Figure 11, the maximum S_{21} emerges at about $H = -3\,\text{cm}$ to $H = -4\,\text{cm}$ when the monopole is in Medium-3, while at about $H = 0\,\text{cm}$ to $H = 0.5\,\text{cm}$ when the monopole is in the Air. That means that the electromagnetic waves radiated by the monopole antenna in the meta-material are refracted downwards of the interface between Medium-3 and the Air. Indeed, if the electromagnetic waves were not refracted downwards, the maximum S_{21} could not emerge at the lower position than the conducting ground plane of the transmitting monopole.

The role of electromagnetic waves diffraction at the edge of the ground plane was also considered. The diffractive electric field below the ground plane of the monopole in the air was calculated. [10] The ground plane is $250 \times 250\,\text{mm}^2$, and the calculated result along the route of the receiving monopole was shown in Figure 12. The diffractive electric field decreases when the position moves downwards below the plane.

Therefore, we conclude that the maximum power detected below the ground plane (at $H = -3\,\text{cm}$ to $-4\,\text{cm}$) when the monopole is in Medium-3 is due to the negative refraction instead of the diffraction.

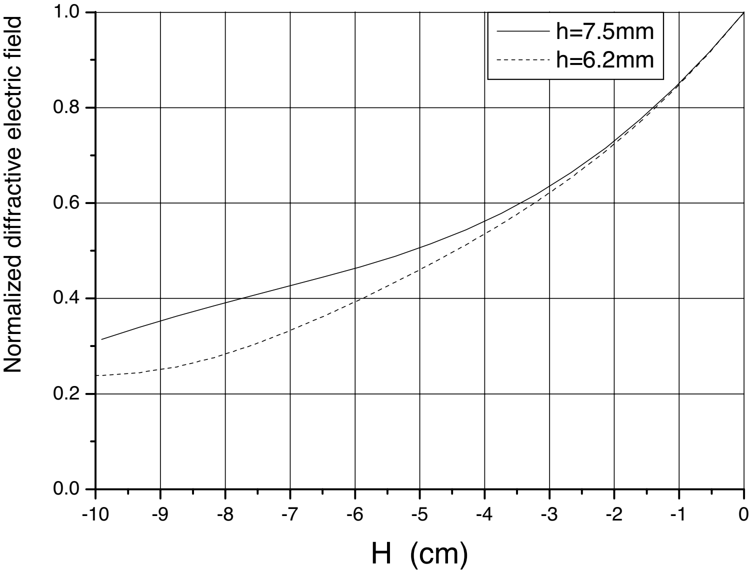

Figure 12. Normalized diffractive electric field.

4. CONCLUSION

The propagation characteristics of the electromagnetic waves radiated by a monopole antenna located inside a meta-material or in the air are studied in our experiments. From the experiments, the following facts can be concluded:

1. The effective permeability of the medium made of SRRs could be negative within 10–10.5 GHz. Both the effective permittivity and the effective permeability of the meta-material with SRRs and strips could be negative within 10.3–10.8 GHz at certain direction.
2. The radiation pattern of the monopole in the meta-material is directional while it is non-directional without the meta-material.
3. The incident beam was refracted on the same side of the normal to the interface between meta-material and the air as the incident ray.

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