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Citation: Journal of Applied Physics **96**, 1979 (2004); doi: 10.1063/1.1767290
View online: http://dx.doi.org/10.1063/1.1767290
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/96/4?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 96, NUMBER 4 15 AUGUST 2004

Electromagnetic resonance in deformed split ring resonators of left-handed meta-materials

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(Received 19 January 2004; accepted 6 May 2004)

Recently, structures called deformed split ring resonators have been proposed to achieve the smallest volume of a unit cell, while retaining negative permeability. With a combination of wire structures, the characteristics of a negative index of refraction, or left-handed meta-materials, can be seen from the transmission spectrum. This electromagnetic resonance, including its orientation tolerance and angular dependence on the incident beam, is explored in detail in the microwave range. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1767290]

I. INTRODUCTION

Recently, the topic of left-handed materials (LHMs) has been under close investigation. The peculiar characteristics and high expectations for the potential applications of LHMs have garnered the attention of many in the scientific community. LHMs known as negative index of refraction materials (NIMs) were first proposed by Veselago[1] in 1968, in which the electric field $\vec{E}$, the magnetic field $\vec{H}$, and the phase velocity $\vec{k}$ of a plane wave formed a left-handed set, i.e., $\vec{k} \times \vec{E} = -w/c_0|\mu|\vec{H}$ and $\vec{k} \times \vec{H} = w/c_0|\varepsilon|\vec{E}$. The wave propagation behaviors of right-handed materials (RHMs), familiar in this scientific field, are reversed in LHMs. For instance, a convex lens made from RHMs has a converging effect, while a lens made from LHMs has an oppositely diverging effect; Doppler shift and Cherenkov radiation are also reversed. Apart from these fascinating properties, Pendry[2] proposed that LHMs could lead waves to break diffraction limits under certain conditions. The theory of LHMs has been well understood for the past thirty years, but it was not until the wire elements and the structure of split-ring resonators (SRRs) were invented by Pendry *et al.*[3–5] in 1999, that further progress was established. Negative index refraction can be exhibited only when effective permittivity ε_{eff} and permeability μ_{eff} are both negative. In the microwave region, when operated frequencies are lower than plasma frequency, negative permittivity ε_{eff} can be obtained with wire elements, which behave like a high pass filter. Negative permeability $-\mu_{\text{eff}}$, on the other hand, can be built into a periodic array of SRRs. Experimental evidence of negative index refraction has been shown, through phase advance measurement[6] and determination by Snell's law, to form a wedge, which assembles arrays of unit cells, comprised of SRRs and wires, to measure the refraction angle.[6–8]

Experiments, involving LHMs, have all been performed so far, within the microwave range;[6–9] most published papers, written on LHMs in the optical range, have focused on numerical simulation or theoretical modeling.[10] It is difficult to implement LHMs in the optical domain due to limitations in fabricating test samples with SRRs structures; this is because shadow mask/etching techniques are limited in developing linewidth of bar patterns. For example, with a linewidth of 0.2 μm, the minimum unit size of an SRR pattern may require at least 1.4×1.8 μm^2. The lattice constant in the x direction will be 1.6 μm (1.4 μm plus a linewidth of 0.2 μm) while in the y direction it will be 2.0 μm (1.8 μm plus a linewidth of 0.2 μm). When applying light at 1.5 μm, its behavior is governed by the grating theory, instead of effective negative permeability; the wavelength of incident light is smaller than the lattice constants in both the x and y directions. In other words, a new structure, to achieve practical implementation, must be considered and developed. In order to reduce the unit size, we recently proposed that deformed split ring resonators DSRRs, whose unit pattern is derived from a simplified version of the original SRR, could have the smallest unit size to preserve effective negative permeability characteristics.[11] A typical DSRR unit cell is shown in Fig. 1(a); it is made from two half deformed split rings, resembling one incomplete split ring with two small gaps. In this article, we report in detail, the behavior of DSRRs printed on a plastic circuit board (PCB) by two-dimensional arrays of unit cells. Our goal is to explore the possibility that DSRRs could be alternative structures, exhibiting effective negative index refraction, when wire elements are attached, for the smallest unit pattern so far. The impact of different orientations and various numbers of arrays will also be discussed in detail.

The article is organized as follows: the experimental setups and resonant spectrums of PCBs, with different sizes of two-dimensional DSRR arrays, in different orientations, are studied in Sec. II; tolerance of the angle included between the sample orientation and the magnetic field of applied microwaves is addressed in Sec. III; the conclusion is presented in Sec. IV.

II. EXPERIMENTAL SETUP AND SAMPLE DETAILS

For the demonstration, we chose the microwave analog approach. The setup for experiments, depicted in Fig. 1(b),

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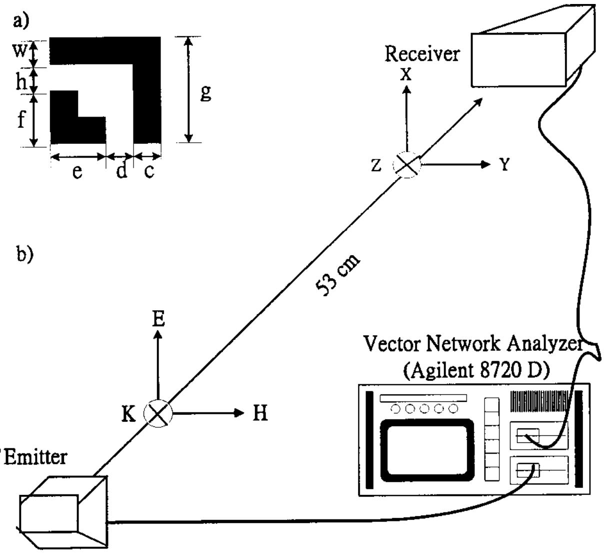

FIG. 1. (a) Schematic diagram of a single deformed-split-ring resonator where c=d=h=w=0.655 mm, e=f=1.31 mm, and g=2.62 mm, (b) the experimental setup, including a coordinate system, where the z axis is along the propagation direction of the Poynting vector, ***S***. ***E*** and ***H*** denote the directions of corresponding electric and magnetic fields for the incident microwave.

remained the same, although the test samples were different. A lens horn antenna (FLANN 16810-FA/16094-SF40; operation range 8.2–12.5 GHz) was used to produce the *x*-axis linearly polarized microwave, which was collimated to propagate along the *Z* axis of the orientation. A time varying magnetic field was applied parallel to the *Y* axis. A standard gain horn (FLANN 17240/16094-SF40; operation range 8.2–12.5 GHz) was used as the microwave receiver, which was located 53 cm from the horn antenna. A vector network analyzer (Agilent 8720D; frequency range 0.05-20.05GHz) was used to examine the responses of these materials to the applied microwaves as well as the performance of the whole experimental system without inserting samples for background identification. To prevent possible interference from reflection during the measurement process, the whole experimental system was inserted in a chamber containing microwave absorbers.

Using a shadow mask/etching technique, we fabricated the printed circuit boards with the DSRRs on one side. The unit cell of the DSRR pattern was 2.62×2.62 mm^2, which is the same size as the original SRR pattern,[6] with the configuration simplified. The working frequency was within the *X* band, i.e., approximately 10 GHz. This enabled our work to more closely correspond to the original SRR experiments.[9] As shown in Fig. 1(a), the spacing lengths denoted by "e" and "f" in the single DSRR pattern are twofold; that of "d," i.e., 1.31 mm=0.655 mm$\times$2. Typical samples were made of many DSRR unit arrays. For instance, there were 20 DSRR cells in one column and 40 rows on one PCB; i.e., 800 DSRR cells in total. The lattice constants of the samples were all 5.0 mm, approximately one sixth of the wavelength in the experiments. The metallic DSRRs and wire strips were made of 0.04-mm-thick copper. The dimensions of sample. A were $10 \times 20 \times 0.06$ cm^3 and the target resonant wavelength was 3.0 cm (frequency 10 GHz). Fiberglass (thickness 0.3 mm) was chosen as the PCB material because of its negligible absorption within the operation range of frequency.

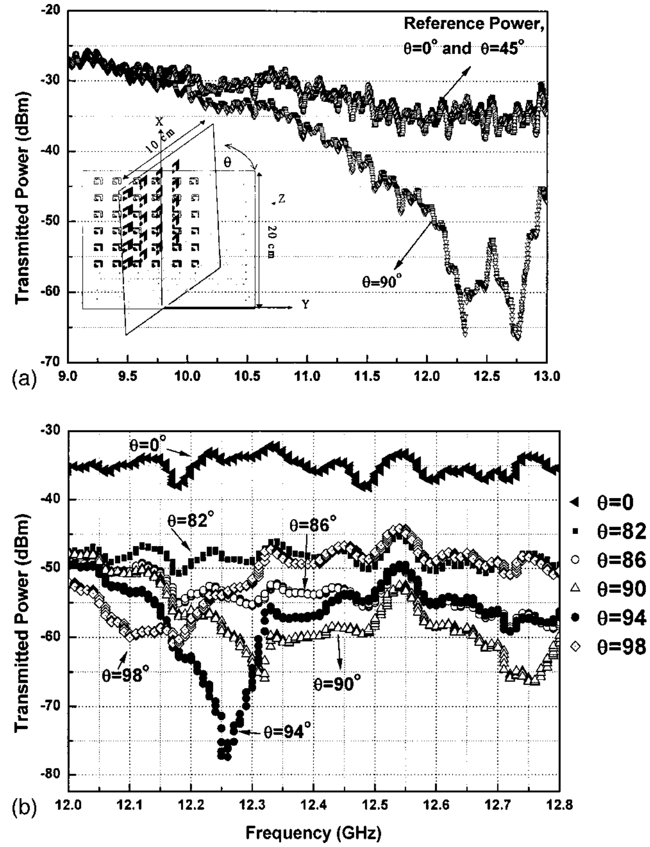

FIG. 2. (a) The transmission radio frequency (RF) spectrums where the results of the free-space case (reference power) denoted by clear upward triangles, sample *A* included at the θ equal to 0 deg, 45 deg, denoted by clear circles and clear squares, respectively. For sample A, θ is equal to 90 deg and is indicated by clear downward triangles showing transmission drop. (b) Transmission spectrums of the sample A when the orientations are different; 0 deg is denoted by the solid triangles, 82 deg by the solid squares, 86 deg by the clear circles, 90 deg by the clear triangles, 94 deg by the solid circles, and 98 deg by the clear diamonds.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The orientation of the sample was very sensitive to the direction of the magnetic field. As shown in Fig. 2(a), the symbol θ is defined as the angle included from the *z* direction to the normal vector of the plane in which DSRR patterns lay. Reference power refers to the power received by the gain horn antenna when the incident wave was propagated in free space without a test sample. It seemed that the incident wave did not sense the existence of the DSRRs pattern when the θ was 0 or 45 deg. Resonant frequency was observed when the θ was 90 deg.

We thoroughly investigated the θ effect. The resonance phenomenon obviously occurred while the θ was in the range between 82 and 98 deg. The θ tolerance was $\pm$12 deg relative to 90 deg, therefore only the results of 82–98 deg are depicted in Fig. 2(b). As θ was outside this range, resonance absorption disappeared, and the experiment became dull, and looked as if no sample had been included. When the θ approached 90 deg, from 82 deg, stronger absorption behaviors were observed and the resonant peak appeared.

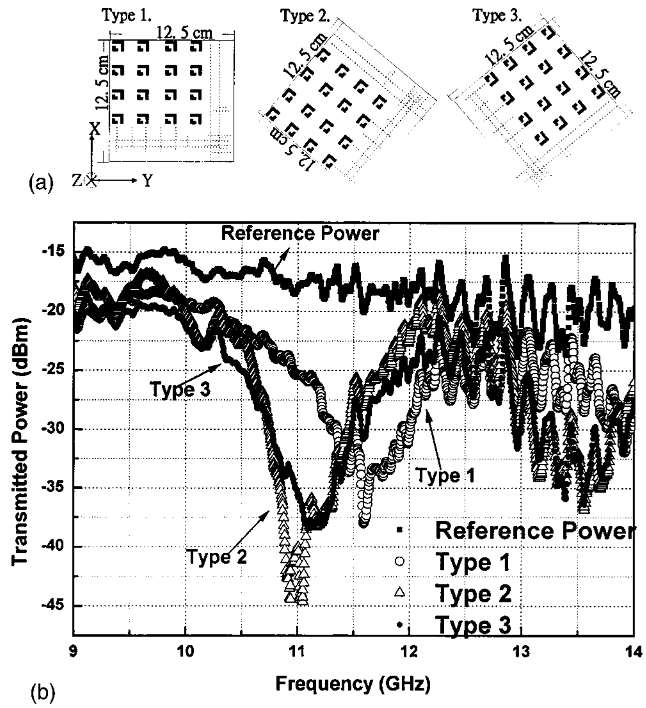

FIG. 3. Transmission spectrums measured for sample B with the different types: 1, 2, and 3. The reference power case is marked as solid squares, type 1 as clear circles, type 2 as clear triangles, and type 3 as solid circles.

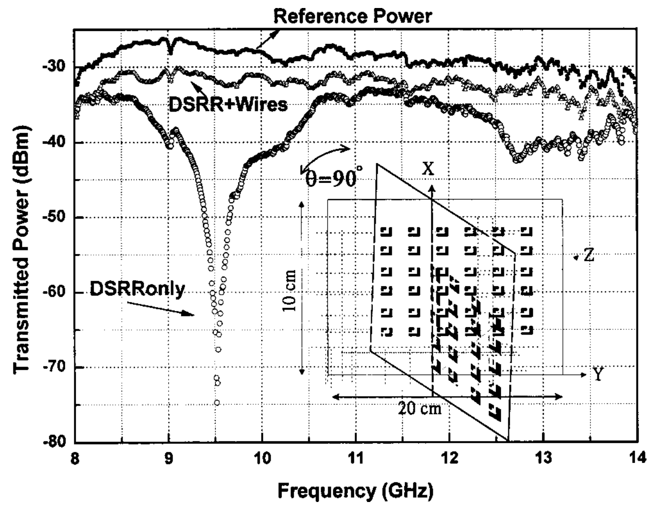

FIG. 4. Transmission spectrums measured for sample A with θ equal to 90 deg. The reference power case is marked as solid squares, DSRRs alone are marked as clear circles; and DSRRs with wires attached are marked as clear triangles.

In order to discuss the resonance from electric field participation, we made another sample B, whose dimension was $12.5\times12.5\times0.06\ \text{cm}^3$ with 25 DSRR cells in one column and 25 rows on one PCB, i.e.; a total of 625 DSRR cells. The DSRR unit size and lattice constant on sample B were the same as those on sample A. Sample B, however, was made symmetrical in order to exclude any possible effects caused by the physical inclusion of numbers of DSRR cells. We rearranged sample B to conform to types 1, 2, and 3 in Fig. 3 then repeated the above experimental procedure. Sample B, lying on the *x*-*y* plane was rotated relative to the x axis. In this case, there was still apparently no resonance absorption when the θ was out of the range. The strongest resonance frequencies appeared when the θ was equal to 90 deg. It can be understood, from this behavior, that the resonance spectrum is caused by the magnetic field. The magnetic field penetrates the DSRR and generates the strong currents flowing through the rings. These currents vanish when in the proximity of the two gaps and produced a strong electric field within the gap.

In this experiment, the influence of the electrical field was weak, because resonance was observed only when the θ was equal to 90 deg. However, the comparison between types 2 and 3, where sample B was arranged with a different orientation of the two gaps in the unit cells, but with the same number of DSRR patterns included and the same cell layout, shows that the resonance spectrums had different absorption levels. The curve of type 2, as shown in Fig. 3, has deeper absorption, with 30 dB at 11 GHz, than type 3. The strong electric field built up in the gaps may join with the incident wave, while the direction of the induced electric field is parallel to the polarization of the incident wave.

To observe the characteristics of the LHMs, we still included the wire elements to our DSRRs patterns in sample A. These wires elements, which were 10 cm long with the same lattice constant of 5 mm, were attached to the sample A. A significant transmission band was exhibited in Fig. 4, which is the same as those in Ref. 11. The resonance frequencies in Fig. 2 and 4 were different; this is due to the orientation of sample A being asymmetrical. It was also observed that different numbers of the unit cells involved caused the resonant peak shift.

The DSRRs pattern exhibited strong resonance when the incident magnetic field penetrated the DSRR and generated strong currents, which flowed on the half rings. Note that this does not happen if the ring is without gaps, i.e., is not split. Nevertheless, the resonance occurred only under some of the conditions referred to above. Based on our results, the tolerance of the angle θ, from the direction of the incident magnetic field to the normal vector of the patterns plane is ±12 deg. In the case where the θ is equal to 45 deg, there is no response. This means that the partial vector of the incident magnetic field, parallel to the normal vector, cannot induce resonance.

The resonant peak will shift if the numbers and the geometrical arrangements of coupling DSRRs are varied, for example, in sample A, which is asymmetrical in numbers of arrays. The experimental results shown in Fig. 2(a) and 4 indicate that different numbers of DSRR unit arrays will make the resonant peak shift, although the orientations of the unit pattern are the same. With larger numbers included in the propagation direction, the resonant peak will have redshifted. The data shown in Fig. 3 demonstrate that the geometrical arrangements of the unit pattern, relative to the incident electric and magnetic field, will also have an influence on the resonant peak shift and the strength of the absorption. It must be emphasized that the electric field may participate in couplings and resonance, when the direction of the electric field built in the gap is parallel to the polarization of the incident wave, even though it is weak. This is consistent with the results inform the original SRR experiments.[9]

IV. CONCLUSIONS

It was believed that a study comparing the patterns of DSRRs and the original SRRs could yield worthwhile information. Intuitively, it is understood that the DSRR pattern is a deformed version of the original SRRs. DSRR have the same electric resonance, a characteristic of the original SRRs, which does not exist in the uninterrupted rings. Besides, the patterns of both the DSRRs, and the original SRRs, can have a transmission band within resonance frequencies, when wire elements are included. Nevertheless, they also differ in many ways. First of all, the unit pattern of the DSRR is comprised of two half deformed split rings, resembling one incomplete split ring; the original SRR, on the other hand, consists of two split rings. The unit size of the DSRR is a quarter the size of the original SRRs. Second, the DSRR pattern characteristics may not be governed by the same formula as the original SRRs, although they both have two oppositely orientated gaps. Apparently, the DSRR pattern does not have a tiny gap between the rings, which determines the capacitance of the original SRRs. In addition, the power loss in transmission band of the DSRR patterns, with wire elements, is much less than the power loss of the original SRR pattern with wire elements.

DSRRs came about mainly because of a motivation to simplify the original split-ring resonator (SRR), and have the smallest unit size while retaining the characteristics of effective negative permeability. As mentioned above, current mask/etching techniques have certain pattern development limitations in terms of the linewidth of a bar pattern. With a linewidth of 0.2 μm, the minimum unit size of a DSRR pattern may require $0.8\times0.8\ \mu\text{m}^2$, the dimensions of which are a quarter of the original SRR pattern. The lattice constants in the x direction would be 1 μm (0.8 μm plus a linewidth of 0.2 μm) and in the y direction, 1 μm (0.8 μm plus a linewidth of 0.2 μm). This greatly enhances the possibilities of exploring the characteristics of negative index refraction in applications of 1.5 μm.

In conclusion, we have shown that a DSRR pattern can increase the possibilities of exploring the characteristics of LHMs in shorter wavelengths. The experimental results indicate that the numbers and geometric arrangements of DSRRs make resonant peak shifts. The resonant peak has redshifted if the larger number arrays included. Our experiments were performed in free space, completely surrounded with absorbing materials to prevent the interference effect. Unlike experimental data with test samples taken from with in the waveguide, our results may be affected by sample size and edge boundary conditions. Our case may be closer to the real situation, however, when the practical devices of the LHMs are implemented.

ACKNOWLEDGMENT

Partial support for this work came from the National Science Council, Taiwan under the Project No. NSC92-2112-M009-040 and from the Ministry of Economic Affairs of Taiwan, R.O.C., under Contract No. 91-EC-17-A-07-S1-0011.

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