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Addendum: "A broadband and high-gain metamaterial microstrip antenna" [Appl. Phys. Lett. 96, 164101 (2010)]

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In a recent paper published,[1] a metamaterial microstrip antenna of broad bandwidth (at about 10 times of the conventional microstrip antenna) and high gain was designed and fabricated; and importantly, the antenna is of end-fire radiation pattern. The special advantages of this kind of metamaterial antennas have drawn considerations from antennas and propagation community, and the results were repeated using the same physical concept and design philosophy.

After the proposed and designed antenna[1] was published, the first author of the paper[1] received continuous queries on the new physics behind good performance of the designed antenna[1] over the last one year. To understand physical insight of the good performance in terms of both broad bandwidth and high gain,[1] we have continued to explore on the physical significance of the meshed microstrip antenna and its coupled meshed ground plane. It is realized recently that the true physics behind the good performance of the antennas of this nature is due to a strong coupling between a meshed top-patch and a patterned ground plane.

According to the transmission line (TL) theory, a single-meshed TL will produce a stopband (as shown in Fig. 1 where a stopband is observed) while a double-meshed TL (ground meshed for producing negative permeability and TL with inter-digital capacitors for producing negative permittivity) could have the passband (as shown in Fig. 2 where a passband is depicted instead). Two patterns, flowers or triangles, are utilized for the ground meshing. It implies that a single-negative (or meshed) TL makes a stopband while a double-negative (or meshed) TL could achieve a passband when the two bandwidths overlap each other.

We have also looked into radiation mechanism of high performance metamaterial antennas and realized that antennas are operated based on the surface wave modes instead of the conventional leaky wave modes. The dispersion curve shows that antennas could have a double-negative bandwidth or a positive bandwidth or both, subject to proper designs. The positive bandwidth occurs at lower frequencies, while the double-negative bandwidth appears at higher frequencies.

Finally, we would like to address the terminology issue of the metamaterial antenna. Nowadays, metamaterials are broadly defined to represent *a large class* of electromagnetic materials including left-handed or double-negative index artificial structures or materials, photonic or electromagnetic band gap (PBG or EBG) materials, anisotropic materials, and various gyrotropic media. Although the dispersion diagram obtained during the antenna design may not always exhibit double negative bandwidth of the designed antenna, the proposal and design of the antenna were inspired by the metamaterial research. We have also looked into physics of obtaining the high performance of the antennas recently.[1] The dispersion curve shows that we do have double negative bandwidth of the proposed single-patch antennas and arrays but they operate at higher frequencies. At the lower frequencies, they are operated based on the surface wave modes instead of the conventional leaky wave modes. Therefore, it is natural to use the terminology of metamaterial antenna for the new idea implementation in the design. The idea implemented[1] can be widely utilized in microwave and optical applications including circuit, waveguide, or antenna

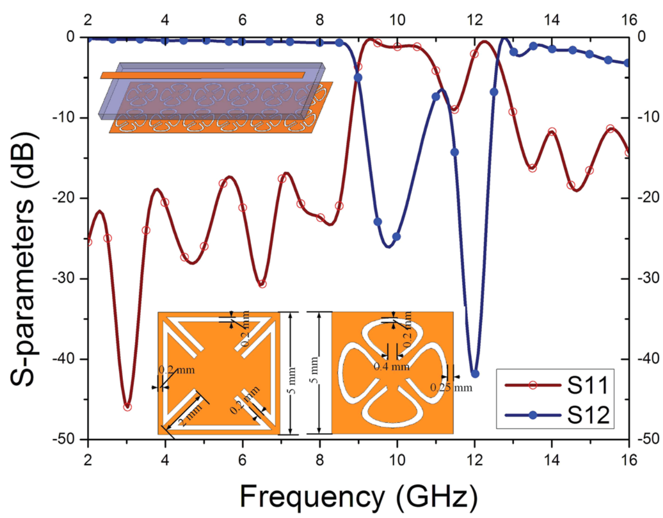

FIG. 1. (Color online) S-parameters, S_{11} and S_{21}, of a ground-meshed TL where a stopband is clearly observed. 12 flower- or triangle-shapes are used for meshing the ground plane. The gap and edge widths are all 0.2 mm, while each size of the unit cell or element is $5 \times 5\ \text{mm}^2$.

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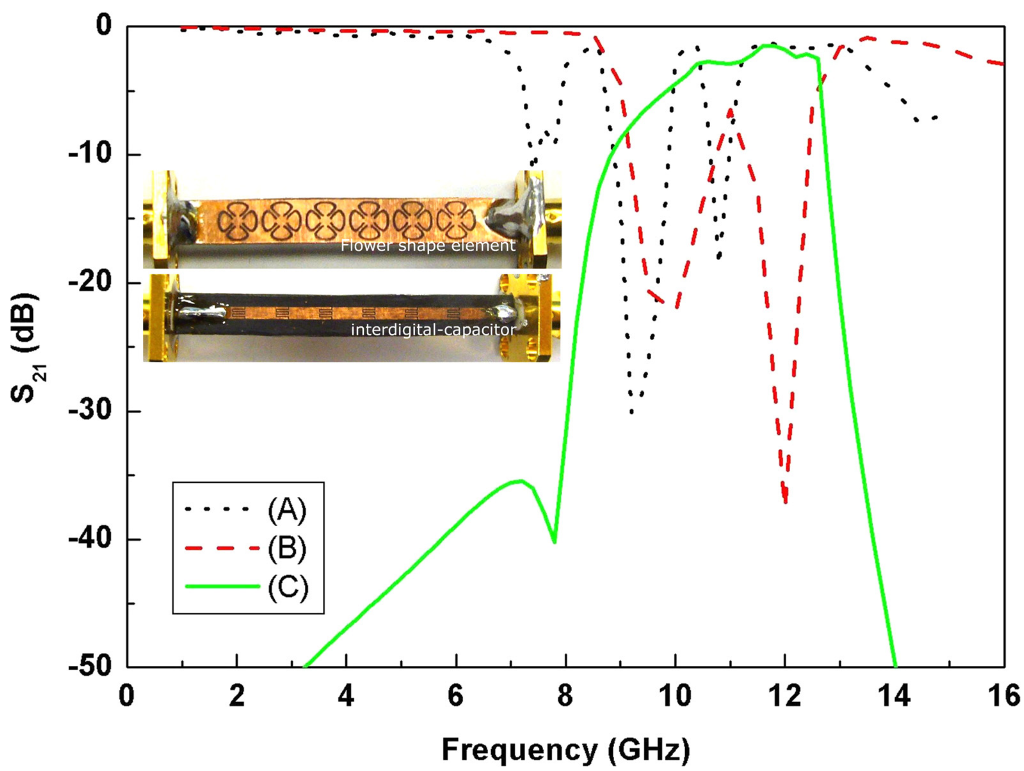

FIG. 2. (Color online) S-parameters, S_{21}, of a TL whose ground is meshed (producing a negative permeability) and whose TL is integrated with an interdigital capacitor (producing a negative permittivity), where a passband is clearly depicted. Three cases are considered, namely, A: TL with triangular shape elements on the ground plane; B: TL with flower shape elements on the ground plane; and C: TL with flower shape elements on the ground plane and interdigital capacitor on the strip line.

designs. The special features are particularly important for practical aero-space applications.

In summary, it is realized from physics point of view and concluded from some recent research work that

(a) the terminology of metamaterial antennas can be utilized, although the dispersion curves of designed antennas or arrays may not exhibit double negative region in the lower frequency region (the double negative region may exist in the higher frequency region);
(b) metamaterial antennas and arrays are operated at lower frequencies primarily based on the surface wave modes that lead to the end-fire antenna radiation; and
(c) surface waves propagate along a strongly coupled transmission line structure which is physically formed from a meshed top-patch and a patterned ground plane with an overlapped frequency (positive or double-negative bandwidth).

It is also noticed that (i) the conventional microstrip antennas and arrays operate based on the leaky-wave or sky-wave modes of narrow bandwidth, and the EBG structures of single negative material nature are usually utilized to suppress the surface wave modes to enhance the antenna radiation efficiency and (ii) in contrast, the metamaterial microstrip antennas and arrays operate based on the surface wave modes of broad bandwidth, and the leaky-wave or sky-wave modes are suppressed through the double-negative nature of meshed antenna elements and patterned ground plane.

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[1]L. W. Li, Y. N. Li, T. S. Yeo, J. R. Mosig, and O. J. F. Martin, Appl. Phys. Lett. **96**, 164101 (2010).