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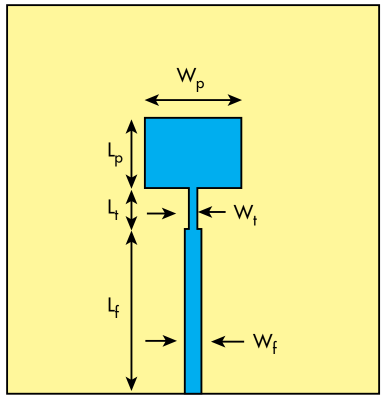
Metamaterial Enhances Microstrip Antenna Gain

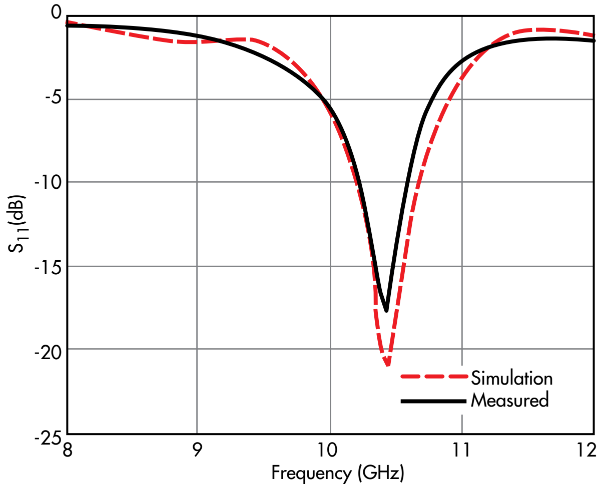
Single and multiple layers of metamaterials formed as lenses can improve the impedance matching, gain, and fractional bandwidth of compact microstrip antennas.

High antenna gain is generally desirable for communications systems, whether terrestrial or based on satellites. The use of metamaterials in single or multiple layers has been shown to contribute a great deal to the design of a high-gain microstrip antenna at 10.5 GHz. With a double-negative electromagnetic (EM) constant, these metamaterials exhibit properties not normally found in circuit materials.

Structures formed of the metamaterials act like a lens for a microstrip antenna, boosting gain and enhancing the radiation pattern for greater coverage. These metamaterial-equipped antenna designs feature increased bandwidth (from 3.64% to 4.68%) when compared to a conventional microstrip design.



1. These are the dimensions of the microstrip antenna.

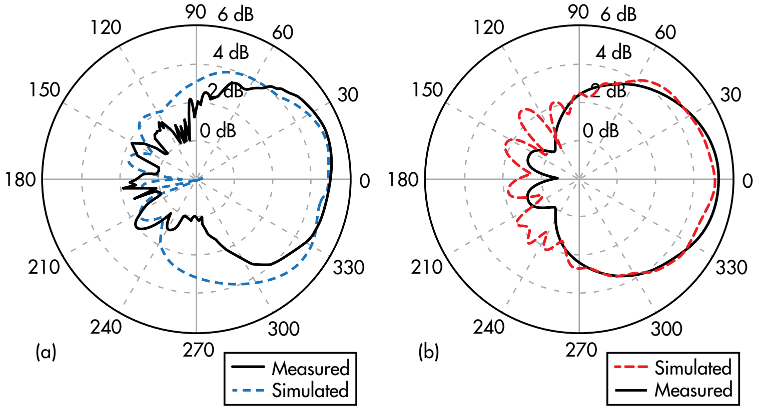


2. The plots compare the simulated and measured return loss of the microstrip antenna, designed for 10.5 GHz.

Patch antennas are often desirable for wireless communications systems for their low profile, compact size, ease of implementation, and low implementation cost. Unfortunately, patch antennas typically exhibit low gain and narrow bandwidths. Several approaches have been presented to overcome these disadvantages.[1-3] For example, arrays of several patch antennas have been used to achieve increased gain. However, this approach must overcome losses associated with the feed network and coupling between antenna elements in the array.

Metamaterials can provide EM properties not found in nature that can help enhance antenna gain. Left-handed materials (LHMs) were theorized in 1967 as EM plane wave propagation in a lossless medium with simultaneous negative real permittivity and permeability at a given frequency.[4] LHM is characterized by antiparallel phase and group velocities as well as nonlinear phase characteristics.[5-7] These properties have enabled the development of compact microwave components.[8-11]

The recent revival of interest in double-negative media began with Smith, Schultz, and Shelby, as inspired by the work of Pendry.[12,13] Smith demonstrated a new metamaterial that simultaneously achieved negative permittivity and permeability.[14] Different shapes of metamaterial cells have also been used to achieve double-negative characteristics.[15-21]

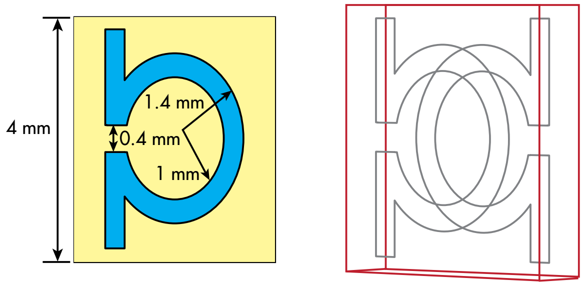


3. The radiation patterns show simulated and measured responses at 10.5 GHz in the (a) E-plane and (b) H-plane.

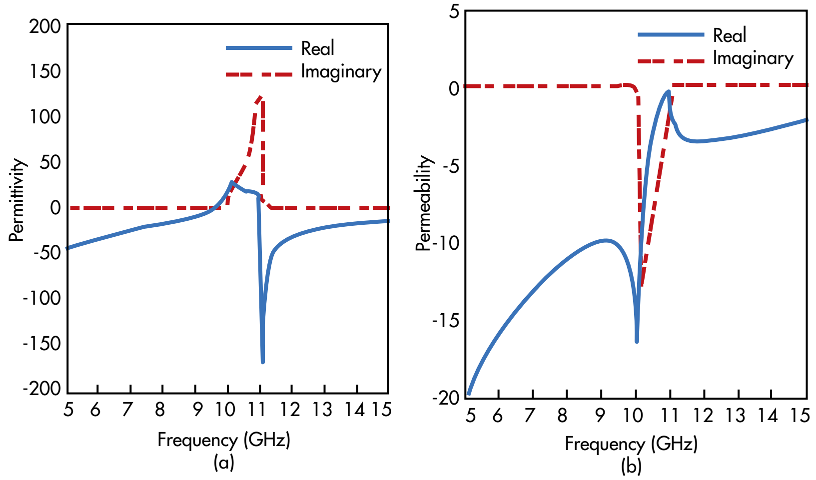
To better understand the benefits of using metamaterial structures with microstrip antennas, an antenna was designed with a unit-cell metamaterial lens structure; the performance of the antenna was evaluated with the Microwave Studio full-wave EM simulation software from CST (www.cst.com). *Figure 1* shows a two-dimensional (2D) layout of the microstrip antenna. It was designed on RT/duroid 5880 circuit material from Rogers Corp. (www.rogerscorp.com) with relative dielectric constant (ε_r) of 2.2 in the z-axis (thickness) at 10 GHz, dielectric loss tangent of 0.0009, and thickness of 0.787 mm.

The optimization of the antenna is carried out using CST Microwave Studio commercial software. The antenna measures 50 × 60 mm. 50 mm × 60 mm. The patch maintains a length, L_p, of 8.8 mm, width, W_p, of 13 mm, and thickness of 35 µm. The antenna is impedance-matched by means of a quarter-wavelength (λ/4) transformer with a length, L_t, of 5 mm and width, W_t, of 0.9 mm. The antenna is fed by means of a 50-Ω microstrip line with a width, W_f, of 2 mm and length, L_f, of 20 mm.

Figure 2 compares measured and simulated values for return loss, which are in good agreement. From the simulations, it is apparent that the antenna has an impedance bandwidth from 10.30 to 10.75 GHz. However, from the measurements, the fabricated antenna exhibits an impedance bandwidth from 10.20 to 10.58 GHz, with a center frequency, f_0, of 10.43 GHz. *Figure 3* shows the antenna's simulated and measured radiation patterns, in the E and H planes at 10.5 GHz, which also agree closely. The measured gain is 5.8 dB.



4. The dimensions of the metamaterial unit cell or lens are shown here.

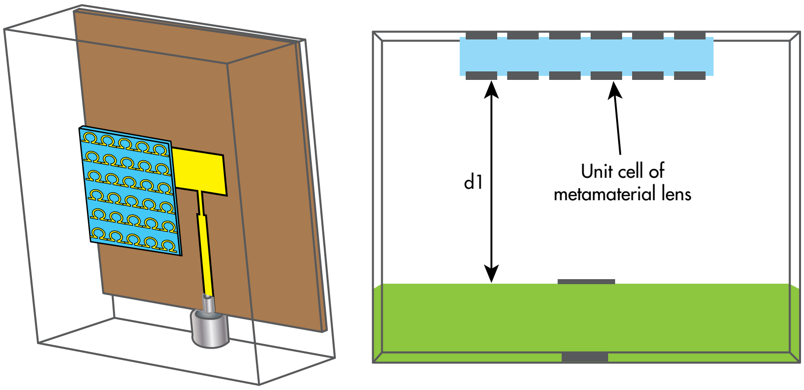


5. The plots show the real and imaginary values for the metamaterial unit cell (a) permittivity and (b) permeability.

Figure 4 presents (a) 2D and (b) three-dimensional (3D) layouts of a single metamaterial unit cell for an omega structure. In this structure, two perfect electric conductors (PECs) with thickness of t = 0.035 mm are integrated on RO4003 circuit material from Rogers Corp. with relative dielectric constant (ε_r) of 3.55, dissipation factor of 0.0027, and thickness of 0.813 mm. This structure is a complex design that couples the rod and ring.[22]

The effective permittivity and the effective permeability of the omega structure can be calculated by an approach based on extraction from the transmission and reflection characteristics of the metamaterial omega structure.[22,23] This extraction technique consists of several steps. First, the complex normalized wave impedance (z) and refractive index (n) are retrieved from the S-parameters. Second, the effective permittivity (ε_{eff}) and permeability (μ_{eff}) are computed from the n and z values. The data are calculated with the aid of the MATLAB mathematics-based simulation software from MathWorks (www.mathworks.com). *Figures 5(a) and (b)* show the effective permittivity and permeability of the omega structure.

To enhance microstrip antenna performance, it was necessary to understand the impact of the size of the omega structure serving as a lens on the radiation patterns and antenna performance. To ensure the



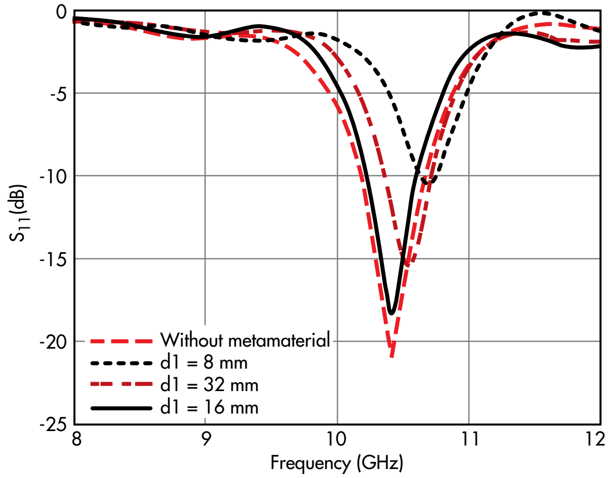
6. This is a simple layout of the microstrip antenna showing the distance to a single-layer metamaterial unit cell.

effect of the periodic structure size and to obtain the optimum return loss and radiation parameters, a parametric study on the antenna loaded with metamaterial lens at specific separation and different dimensions for the periodic structure are carried out.[24] A 6 × 5 periodic structure was considered optimal.

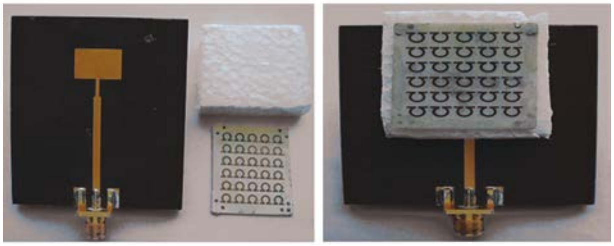
Figure 6 shows the antenna layout, with a single-layer metamaterial lens loaded at a distance, d1, from the patch antenna. The effect of d1 on performance was evaluated, with simulated return loss and gain for different values of d1 shown in *Figs. 7 and 8.*

When d1 equals 8 mm, at around $0.25\lambda_0$, the impedance bandwidth and gain are affected compared to the antenna without metamaterial lens, where the bandwidth and gain are less. When d1 equals 16 mm, at around $0.50\lambda_0$, the impedance bandwidth and gain are increased.

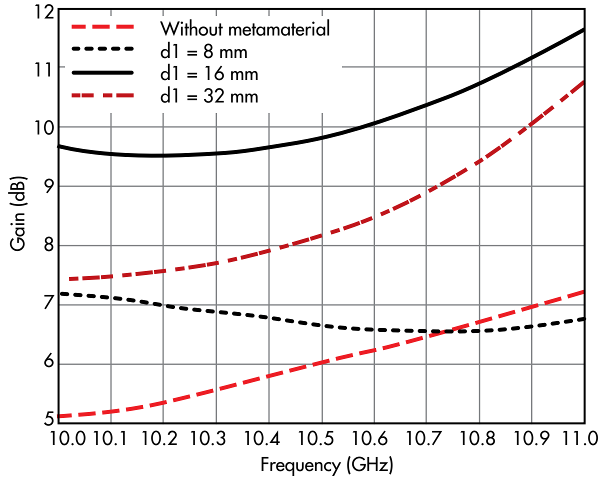
When d1 is increased to 32 mm, at around $1.0\lambda_0$, the impedance bandwidth is reduced and the operating frequency is shifted toward 10.7 GHz. The gain is reduced to 8 dB, but it is still more than a conventional antenna without metamaterial lens. For optimum performance with a single-layer metamaterial lens,



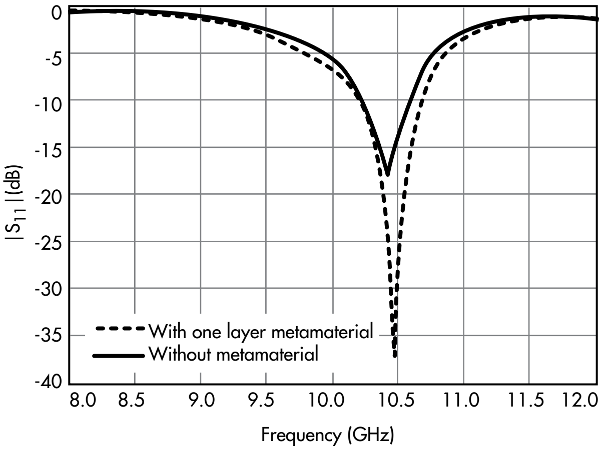
7. The plots show the simulated return loss of the microstrip antenna with a single-layer metamaterial lens at different values of distance d1.



9. These photographs show different views of the fabricated antenna with a single-layer metmaterial lens.



8. These plots show simulated gain for the microstrip antenna with a single-layer metamaterial lens at different values of distance d1.



10. The return loss of the microstrip antenna was measured with and without a single-layer metamaterial lens.

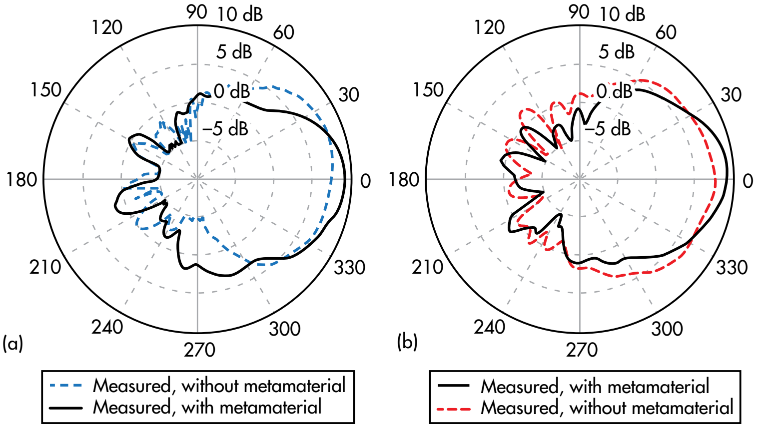
d1 should be equal to 16 mm at this frequency.

To better understand the effects of the metamaterial structure, the proposed antenna was fabricated and characterized. Foam material with relative dielectric constant approximately equal to that of air (1) and thickness (d1) was added as a spacer between the metamaterial and the patch antenna *(Fig. 9)*.

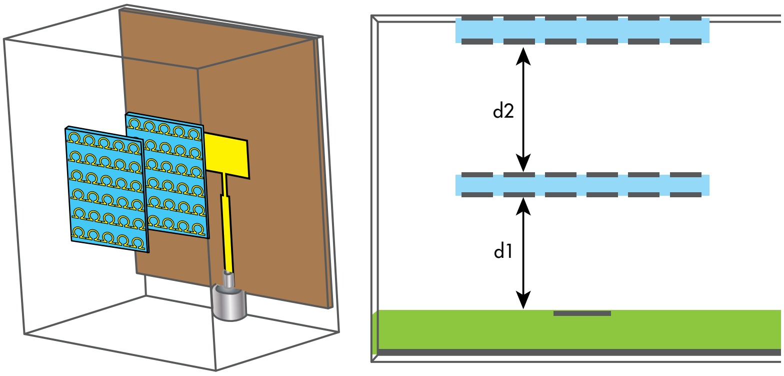
Figure 10 shows measured return loss with and without the metamaterial. As can be seen, the metamaterial lens enhances the matching characteristics of the antenna. The fractional bandwidth of the antenna is increased from 3.64% to 4.68% as well. *Figure 11* shows the measured E- and H-plane radiation patterns of the antenna at 10.5 GHz.

If one metamaterial layer can help microstrip antenna performance, perhaps two layers might provide greater benefits. To explore this possibility, the effects of adding another layer of metamaterial were investigated, at a distance, d2, from the first layer above the antenna. An optimum value of d1 = 16 mm was used for the first layer. *Figure 12* shows the proposed antenna with two metamaterial layers.

The second layer was placed at different distances of 0.25λ_0, 0.55λ_0, and 5λ_0 above the first layer, with simulated return loss and gain plotted in *Figs. 13 and 14*, respectively.



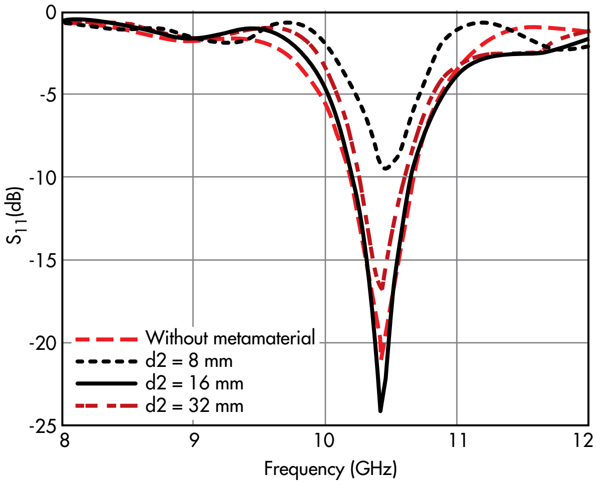
11. The gain of the microstrip antenna was at 10.5 GHz with and without metamaterials in (a) the E-plane and in (b) the H-plane.



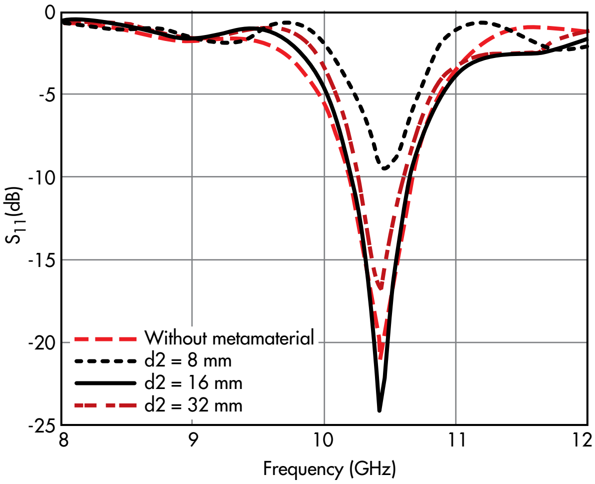
12. This layout shows the concept of the microstrip antenna with two metamaterial lenses on the left and the spacing of the lenses on the right.

With the added metamaterial layer, the gain of the antenna increased from 5.8 to 12 dB at 10.5 GHz. It also increased from 11.8 to 12.4 dB at the lower-frequency edge of the band at 10.3 GHz and at the upper-frequency edge of the band at 10.7 GHz at a distance of d2 = 16 mm for high gain throughout the antenna bandwidth. When d2 = 32 mm, the gain of the antenna increased from 5.8 to 11.4 dB at 10.5 GHz. The optimum distances d1 and d2 for good antenna performance in the 10-GHz band were d1 = 16 mm and d2 = 16 mm.

For references, see the version of this article at www.mwrf.com.



13. The antenna return loss was simulated for different values of distance d2.



14. These plots compare the simulated gain of the microstrip antenna without a metamaterial lens and with different values of distance d2.