Directivity and Bandwidth Enhancement of Proximity-Coupled Microstrip Antenna Using Metamaterial Cover

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Abstract **─** Two major problems associated with patch antennas are low gain and narrow bandwidth. This paper is mainly concerned with directivity and bandwidth enhancement of proximity-coupled microstrip antenna using metamaterial cover. Compared to the patch without metamaterial cover, bandwidth of the antenna is improved about 2.33% and directivity is increased about 9.91dB. The commercial software CST Microwave Studio and a full-wave FDTD numerical technique, developed by the authors, are adopted for the simulations.

Index Terms **─** Metamaterial cover, FDTD.

I. INTRODUCTION

Directive patch antennas are very popular in electromagnetic community. Their attractive features, such as low profile, light weight, low cost and compatibility with MMICs, do not exist in other antennas. Two distinctive types of directive antennas are parabolic antennas and large array antennas. Bulk and curved surface of parabolic antennas limits their use in many commercial applications. Also, complex feeding mechanism and loss in the feeding network are two major disadvantages associated with microstrip array antennas [1]. One solution to these problems is to use metamaterial cover over the patch antenna [2-5]. One of the first works was done by B. Temelkuaran in 2000, [6]. In 2002, S. Enoch proposed a kind of metamaterial for directive emission, [7]. Another problem associated with microstrip antennas is their narrow bandwidth. The previous works so far [3-5] have dealt only with the enhancement of the antenna directivity using metamaterial cover, but the effect of this cover on the antenna input impedance has not been investigated. Recently, a new metamaterial cover has been proposed to enhance both the antenna bandwidth and directivity, [8]. But, its directivity is significantly lower compared to the primary metamaterial cover, [2-5]. In this paper, we have demonstrated that both the antenna impedance bandwidth and directivity can be enhanced using the metamaterial cover over the proximity-coupled patch antenna. It is known that proximity-coupled patch antennas are sensitive to the transverse feed point location. In this paper, a parasitic microstrip line has been used on the opposite side of the feed line to mitigate this drawback. Our new configuration not only increases the antenna directivity from 6.25dB to 16.16dB (at the center frequency), but also increases the impedance bandwidth of the patch antenna from 2.9% to 5.23%. In this paper, we first investigate the impedance bandwidth of the antenna using its resonant frequencies and then examine 3dB directivity bandwidth of the proposed antenna.

II. METAMATERIAL DESIGN

A schematic of the metamaterial cover is shown in Fig. 1. It consists of two planar layers with similar square lattices. It was demonstrated in

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[9-10] that in the frequency range, where the wavelength is very large compared to the period of the periodic cover, this structure acts as a homogenous medium whose equivalent refractive index in the microwave domain is given by

$$n_{eff} = \sqrt{1-\left(f_P/f\right)^2} \quad (1)$$

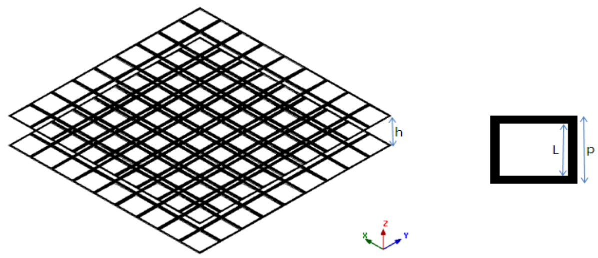


Fig. 1. Schematic view of two-layer metamaterial cover.

Where f_P denotes the plasma frequency and f denotes the operating frequency. If the operating frequency is selected slightly larger than the natural plasma frequency, the equivalent refractive index will be extremely low. Consequently, the transmission phase at the plasma frequency is extremely low [2]. The ultra refraction phenomena can be expected where the transmission coefficient reaches its maximum value [2, 7]. In other words, the zero transmission phase occurs at the same frequencies where the magnitude of the transmission coefficient becomes maximum. Hence, it acts similar to an equally phase surface at its plasma frequency [2]. It is evident from Equ.1, that the equivalent refractive index and thus the antenna directivity are very sensitive to the frequency.

However, these significant changes in the antenna directivity with respect to the frequency represent the potential challenges in the design and application of these metamaterial superstrates in antenna engineering. The transmission characteristic of the metamaterial cover has been investigated, without the ground plane and without the antenna, using FDTD code developed by the authors. Its effective unit cell model is shown in Fig. 2. The normalization in the code consists of choosing the peak magnitude of the transmission coefficient to be unity. Therefore, the magnitude of the transmitted field from the metamaterial cover has been normalized to that without the metamaterial cover. We have used the same methodology applied in the measurements [7]. Since an infinite periodic structure has been simulated, the peak magnitude of the transmission coefficient is unity, unlike the results obtained in the measurements [7]. The dimensions of the analyzed metamaterial cover are:

P=0.41λ_{6GHz}, t = 0.01 λ_{6GHz}, L= 0.31λ_{6GHz}, h=0.49λ_{6GHz}

Where λ_{6GHz} (50mm) denotes the free space wavelength at 6GHz, P is the periodicity, t is the thickness of the metallic grids, L is the edge of the square holes and h is the distance between the two sheets which is the same as the distance between the patch antenna and the first sheet. In the FDTD simulations, a uniform 0.01λ_{6GHz} grid size is used. The resulting transmission curve is also plotted in Fig. 3.

As can be seen, this structure possesses three microwave plasma frequencies at about 5GHz, 5.81GHz and 8.1GHz which make it suitable for the antenna applications. When the aforementioned metamaterial based cover is placed over the conventional proximity-coupled patch antenna, the final metamaterial antenna can be approximated by a homogenous medium terminated in a ground plane, [9-10].

This approximation is similar to that used for the transmission coefficient calculations, as used also by other authors [3, 5, 7]. It is a simple matter to obtain the surface impedance of this grounded slab as a function of metamaterial parameters. A surface impedance of the grounded slab of thickness h is:

$$Z_s = j\eta \tan(2\pi h/\lambda) \quad (2)$$

Where η and λ are the wave impedance and wavelength in the slab, respectively. For the extremely low value of ε_{eff} the surface impedance is very low and inductive. In addition, the inductive reactance is X_l=$j\omega L$. For equivalence we can equate them, leading to the following equation:

$$j\omega L = j\eta \tan(2\pi h/\lambda) \quad (3)$$

Since $\varepsilon_{eff} << 1$, we can apply the small-angle approximation, so that above equation then becomes $L=\mu_0 h$. Consequently, the operation mechanism of this metamaterial based cover can be explained using this equivalent inductance. In addition, coupling between the feed line and the patch antenna is totally capacitive [1]. And thus, one can expect another resonant frequency due to the reactive cancellation between the capacitive feeding structure and the inductive metamaterial cover. Consequently, an appropriate selection of the coupling capacitor value can result in a broadband operation.

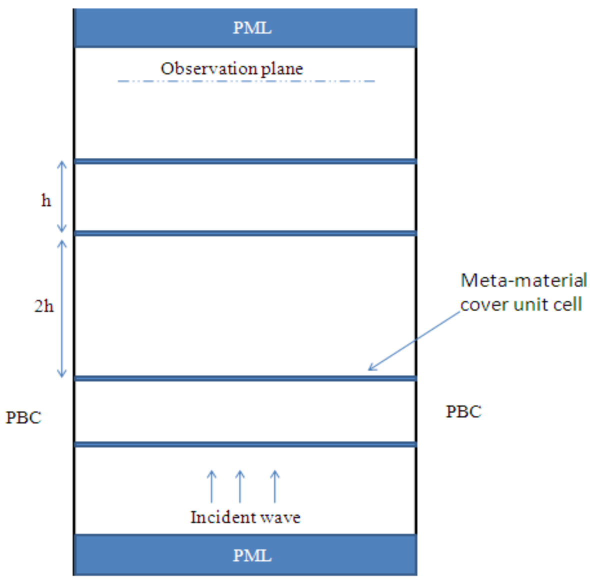


Fig. 2. FDTD model for transmission band selection of a metamaterial cover.

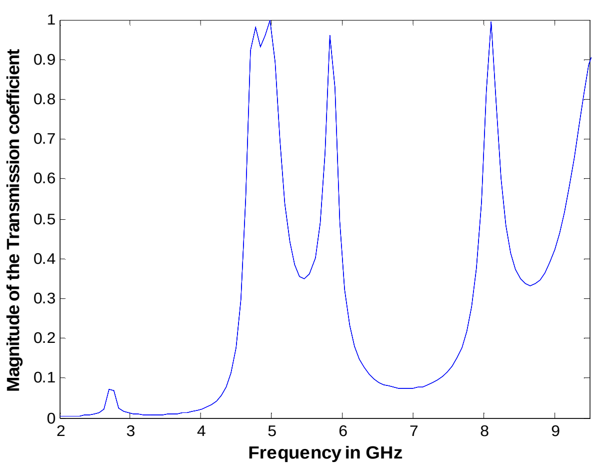


Fig. 3. FDTD simulated transmission of metamaterial cover.

III. ANTENNA CONFIGURATION AND SIMULATION RESULTS

For the purpose of realization, the metamaterial cover described in the previous section is placed over the conventional proximity-coupled patch antenna. A schematic of proposed metamaterial patch antenna is shown in Fig. 4. In general, the two dielectrics can be of different thicknesses and relative permittivity, but here both dielectrics are 30mil (h_1=h_2= 0.762mm) Duroid with, ε_r= 2.2. For the case discussed here, the patch of the antenna is rectangular with 12.45mm width and 16mm length. The distance between the main microstrip line and the parasitic line is also 7mm. Each metamaterial cover composed of 9×9 unit cells, as shown in Fig. 4. Consequently, the total size of the dielectric substrate and the metamaterial cover is 184.5mm×184.5mm. Furthermore, the working frequency of the conventional patch antenna is selected at 5.9GHz.

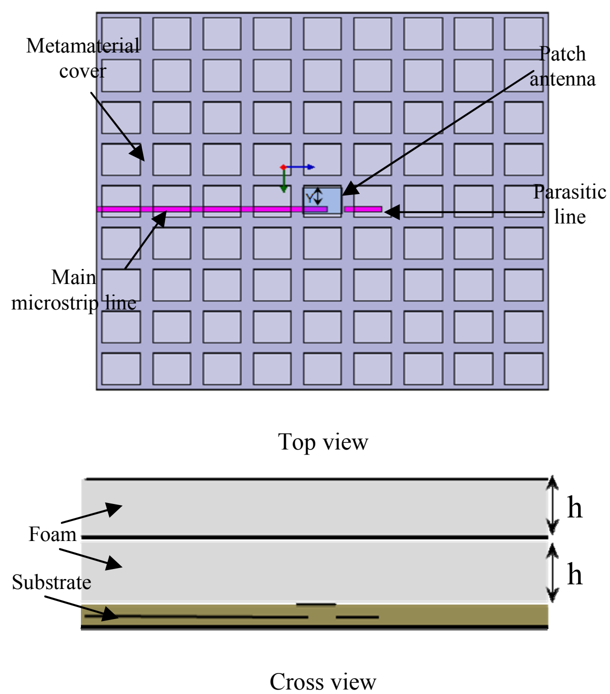


Fig. 4. Geometry of a metamaterial proximity-coupled patch antenna: Y=9mm.

Return loss of the proposed metamaterial patch antenna has been simulated and was compared to the one obtained for the conventional proximity-coupled patch antenna in Fig. 5. As revealed in the figure, the antenna return loss is significantly improved compared to the reference patch antenna without the metamaterial cover. The impedance bandwidth of the patch antenna is increased from 2.9% to 5.23% (ranging from 5.649GHz to 5.952GHz). Using the usual formulas mentioned in [1], the conventional proximity-coupled patch antenna discussed here possesses a TM_{01} mode resonant frequency of approximately 5.9GHz. The second resonant frequency of the metamaterial patch antenna is obviously due to the TM_{01} mode of the conventional patch antenna. (See Fig. 5) Since the metamaterial superstrate disturbs the current distribution of the TM_{01} mode, this resonant frequency slightly shifts down to a lower frequency. An interested reader is recommended to refer to [11] for more details. The first resonant frequency is the result of reactive cancellation between the capacitive feeding structure and the inductive metamaterial cover. On the other hand, the first resonant frequency is close to the second resonant frequency, which results in broadband operation. The simulation results of Fig. 5 are in good agreement with the theoretical predictions discussed in the last paragraph of the previous section, which serve to justify the approximations that were used to model the metamaterial patch antenna as a grounded homogenous medium. It is necessary to mention that the parasitic line section, used on the opposite side of the feed line, stabilizes the antenna performance at its resonant frequency at the expense of an additional resonance frequency at about 6.24GHz. A detailed discussion on that will be presented in a future work.

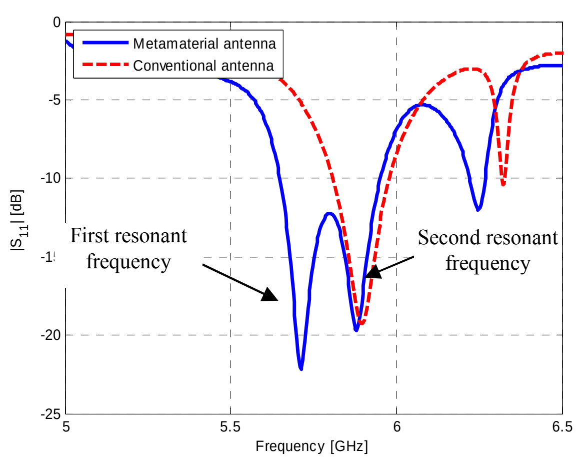


Fig. 5. Simulated return loss versus frequency.

By using the metamaterial cover over the patch antenna, the antenna radiation patterns in E- and H-planes are concentrated in a direction perpendicular to the patch antenna (θ=0).

The simulated broadside directivity versus frequency is shown in Fig. 6. As can be seen, the maximum directivity of the patch antenna is increased from 6.25dB to16.16dB using metamaterial cover. The 3dB directivity bandwidth of the metamaterial antenna is also between 5.685GHz and 5.91GHz, or 3.88%.

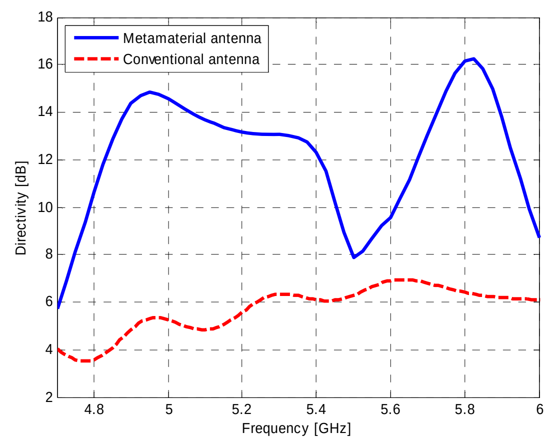
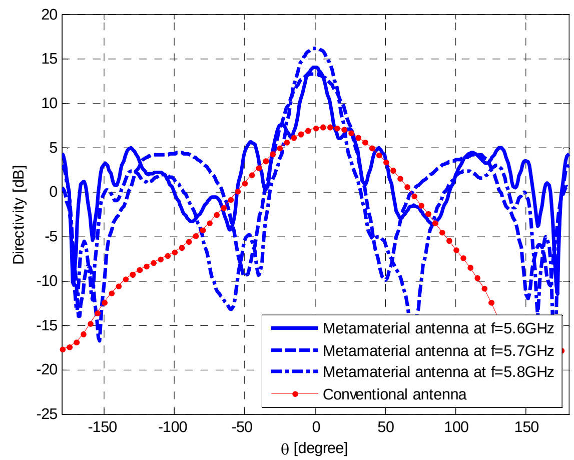
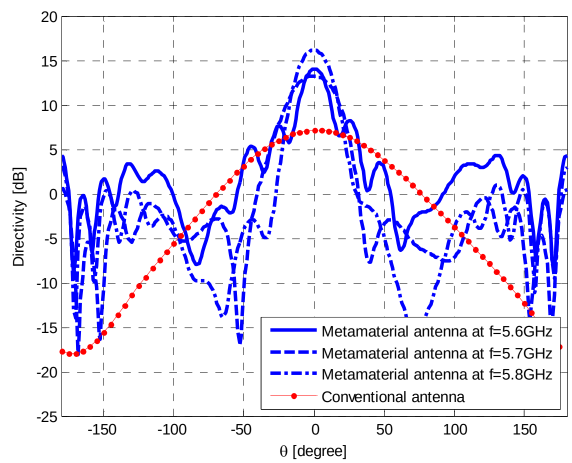


Fig. 6. Simulated broadside directivity versus frequency.

The antenna radiation patterns within its bandwidth are also investigated. The E-plane and H-plane patterns of the metamaterial patch antenna at three frequencies (5.7GHz, 5.8GHz and 5.9GHz) have been simulated and were compared to the one obtained for the conventional antenna, at 5.9GHz, in Fig. 7. Although the radiation pattern of the metamaterial antenna changes a bit at each frequency, the main lobe of the metamaterial antenna at all frequencies (ranging from 5.65 to 5.95GHz) is in the broadside direction and maximum directivity is reasonably good. In the present case, the area of the aperture is A=184.5mm×184.5mm, and $\lambda=c_0/f_0$= 51.724mm, so that maximum directivity then becomes D_{max}= 22dB. The maximum directivity of the metamaterial patch antenna, occurring at 5.81GHz, (16.16dB) has approached the maximal directivity obtained, theoretically, with the same aperture size. In addition, we have investigated the effect of parasitic strip on the antenna return loss.



(a)



(b)

Fig. 7. CST simulated radiation patterns at different frequencies over the operating bandwidth, (a) E-plane, and (b) H-plane.

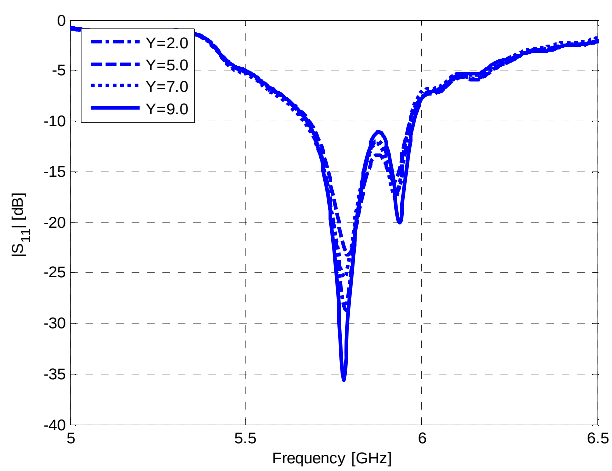


Fig. 8. Return loss of the metamaterial antenna v.s. frequency for the different feed point locations (*Y* in mm).

Consequently, the transverse feed point location is changed from one side of the metamaterial patch antenna to the other side. The antenna return loss versus frequency is shown for the different values of *Y* in Fig. 8. As can be seen, displacement of the feed point location does not have a considerable effect on the antenna input impedance and bandwidth, [13].

IV. CONCLUSION

A new metamaterial proximity coupled-patch antenna has been proposed, which is not sensitive to the transverse feed point location. A full-wave FDTD numerical method has been developed for designing and characterizing metamaterial cover. Proximity-coupled patch antenna has been designed and simulated to demonstrate the potential application of this metamaterial cover. Compared to the conventional design both the antenna impedance bandwidth and directivity increase about 2.33% and 9.91dB, respectively. The 3dB directivity bandwidth of the proposed metamaterial patch antenna is about 3.88%. Furthermore, the antenna bandwidth can be also increased by tuning the length of the parasitic strip.

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