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NOVEL DESIGN OF TRIPLE BAND RECTANGULAR PATCH ANTENNA LOADED WITH METAMATERIAL

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Abstract—In this paper, for the very first time, triple band rectangular patch antenna loaded with metamaterial has been reported. Maximum directivities demonstrated here for all the three bands are quite high in comparison with previously reported any kind of rectangular patch antenna. This unique triple band performance has been achieved with the help of newly produced $TM_{0\delta 0}$ ($3 < \delta < 4$) mode, symmetric slot loading and parasitic patch adjustment. Application of etched slot and parasitic patch in DPS (double positive)-metamaterial juxtaposed layer loaded antenna has been also demonstrated for the first time. Considering the quite satisfactory performance (S-parameter, radiation pattern and radiation efficiency) of this novel design, we expect that our proposed ideas will be very effective to design all these metamaterial loaded novel rectangular patch antennas.

1. INTRODUCTION

Artificial materials (metamaterials) with unusual electromagnetic properties have received a growing amount of interest in recent years [1]. In modern satellite based communication system, better directivity performance is a very important factor. Metamaterial based antennas show very good directivity [2, 3]. Normally, dual frequency patch antennas provide an alternative to large bandwidth planner antennas. When the two operating frequencies are far apart, a dual

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frequency patch structure can be conceived to avoid the use of separate antennas [4]. In radar and communication system applications a unique radiating structure is desirable to accomplish all these above mentioned operations. In this paper, for the very first time, we are going to introduce novel concept of successful triple band rectangular patch antenna using SNG (single negative) metamaterial.

In [5], we have proposed a general algorithm to design SNG (both ENG (ε-negative) and MNG (μ-negative)) metamaterial loaded rectangular patch antennas. In this paper, using that novel algorithm, for the very first time we will show the novel designs of triple band rectangular microstrip patch antennas partially loaded with ENG metamaterial. Here, in Section 3, we will use newly introduced $TM_{0\delta 0}$ mode(s) ($3 < \delta < 4$) for triple band application. Interestingly, it will be shown that these unconventional very high $TM_{0\delta 0}$ modes will give quite satisfactory radiation patterns (directivity above 7 dBi at broadside for each modified mode) due to proper use of our previously proposed algorithm [5], symmetric slots and parasitic patch. Moreover, this contribution will be the first example of using 'etched slot' successfully in a metamaterial loaded rectangular patch antenna. Later, in Section 4, we have given possible explanation of the new observations regarding our proposed novel triple band design.

2. GENERAL FORMULATION

In Figure 1, the geometry of an un-slotted patch antenna with metamaterial block is shown. It consists of a metallic patch with transverse dimensions ($L_p \times W_p$) placed over a ground plane (distance h). The underneath substrate (which is $L_p \times W_p \times h$ in volume) is inhomogeneous, filled with two isotropic and homogeneous materials

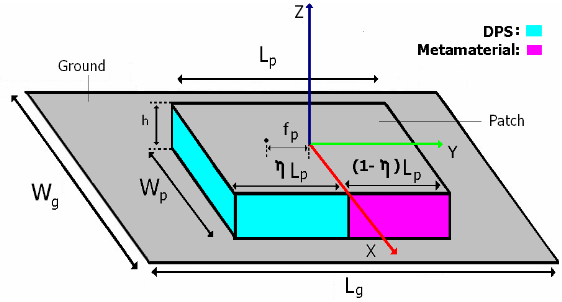


Figure 1. Geometry of a rectangular microstrip patch antenna partially loaded with metamaterial (ENG, MNG or DNG). f_p = feed position from DPS and metamaterial interface.

with permittivity and permeability ϵ_1, μ_1 and ϵ_2, μ_2. The filling ratio of the DPS is η (i.e., the length of DPS block under the patch is ηL).

The key points to run the algorithm [5] for designing a rectangular microstrip patch antenna loaded with ENG metamaterial (Outputs will be ε_2 and η at f_r):

1. $k_1\eta L$ Range for ENG metamaterial loading: $180^\circ < k_1\eta L_p < 225^\circ$.
2. $\sqrt{\frac{\epsilon_1}{\mu_1}}\tan(k_1\eta L_p) - \sqrt{|\frac{\epsilon_2}{\mu_2}|}\tanh(|k_2|(1-\eta)L_p) =$ within 0.000001 to -0.000001 (Additional resonance condition).
3. $E_{z_1} = E_0\cosh(|k_2|(1-\eta)L_p) \& E_{z_2} = E_0\cos(k_1\eta L_p)$ [at two radiating edges].
4. $-1 < r < -0.7$, where $r = E_{z2}/E_{z1}$ (modified mode or broadside radiation condition).

In Figure 2 of [5], we have shown that ENG metamaterial is applicable to produce additional modified mode when $180^\circ < k_1\eta L < 225^\circ$ relation is satisfied. We have found that using $TM_{0\delta0}$ $(1 < \delta < 2)$ mode (as $k_1\eta L 180^\circ$) it is possible to get frequency ratio maximum 1.5 for dual band designs independent of antenna size. These antennas will show quite satisfactory dual band performance (from the point of view of S-parameter, radiation pattern and radiation efficiency performance). But designing a triple band rectangular patch antenna is a very challenging task. In this paper, for the very first time, a triple band rectangular patch antenna loaded with metamaterial has been proposed. We are unable to refer such a triple band rectangular patch antenna because triple band antennas found in previously reported literature do not fall into the category of 'rectangular microstrip patch antenna'. Moreover, satisfactory radiation pattern and directivity performance have not been found in previously reported design of any triple band antenna. However, we are going to introduce a complete different approach for designing a triple band rectangular patch antenna with quite satisfactory radiating performance.

3. NOVEL DESIGN OF TRIPLE BAND RECTANGULAR PATCH ANTENNA

In [6], Xiong et al. have predicted that any etched slot in the metallic patch may deteriorate the performance of a metamaterial loaded rectangular patch antenna. But in this current contribution, we are going to use two symmetrical etched slots as in [7] to introduce the novel concept of additional modified $TM_{0\delta0}$ $(3 < \delta < 4)$ mode(s). Here, we have adopted a 40 mm × 35 mm patch (Figure 2) to design such an antenna. Surprisingly, these etched slots have not deteriorated the

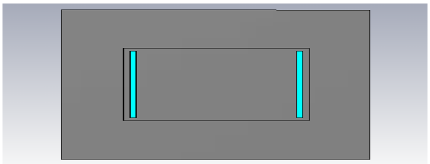


Figure 2. A 40 mm × 35 mm DPS loaded microstrip patch antenna with symmetrical slots proposed by Maci et al. [7].

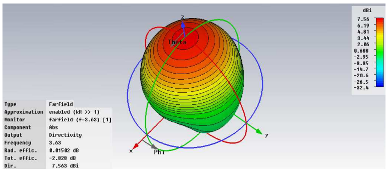


Figure 3. Modified TM_{030} mode 3-D radiation pattern of antenna shown in Figure 2.

performance of our proposed triple band rectangular patch antenna. At first, Maci et al. [7] have used the idea of symmetrical slots at the two radiating edges of a rectangular patch antenna to get dual band performance. These symmetrical slots are responsible for the modification of the 'TM_{030} mode current distribution' over the patch. As a result, TM_{030} mode acts as TM_{010} mode and the antenna successfully demonstrates dual band performance. But we will utilize these symmetrical slots in our proposed antenna to achieve triple band performance.

Using the relation $180° < k_1 \eta L < 225°$ and our proposed 'Design Algorithm' [5], we have been able to introduce modified $TM_{0\delta 0}$ ($3 < \delta < 4$) mode(s) successfully. At first, using proposed idea of Maci et al. [7] and taking $\epsilon_r = 2.2$, we find TM_{010}, TM_{030} and TM_{040} at 2.41 GHz, 3.63 GHz and 6.36 GHz respectively. TM_{030} mode is found modified here. But modes higher than TM_{030} mode are quite different and show dissatisfactory radiation performance as TM_{020} mode (broadside null). To introduce an additional modified mode, we have chosen $f_r = 4.7$ here. Then using our proposed 'Design Algorithm' [5] (see Figure 5), we have derived our design parameters (Table 1). Lorentz dispersive lossy model [8, 9] used in this design is shown in Figure 4 with necessary parameter values. Using 'CST MICROWAVE STUDIO' [10] based full wave analysis; we have found an 'interface resonance' mode at 5.08 GHz. Unfortunately this type of antenna is not usable because of poor bandwidth performance (Figure 7(a)). As a result, our next target was to enhance bandwidth with proper 'impedance matching' ($|S_{11}|$ below -10 dB) and also maintain satisfactory radiation pattern. 'Impedance matching' technique and bandwidth enhancement of a rectangular patch antenna loaded with metamaterial have been discussed in [11] and [12] respectively. But using those techniques ([11] and [12]), the radiation performance deteriorates severely. Actually, these approaches are not applicable in any kind of rectangular patch antenna

Table 1. Chosen parameters after applying 'Design Algorithm' of [5].

Chosen resonant frequency, f_r	ϵ_2 (at f_r)	η	$\frac{E_{z2}}{E_{z1}}$ (at edge boundaries)
4.7 GHz	−0.1111	0.5576	−0.8462

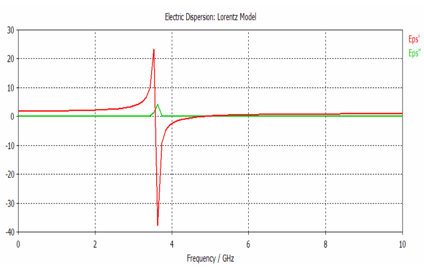


Figure 4. Lorentz model of the ENG metamaterial used in antenna shown in Figure 6. Here, $\delta = 50\,\text{MHz}$, $\omega_0 = 22619467110\,\text{rad/s}$, $\epsilon_s = 1.7827$.

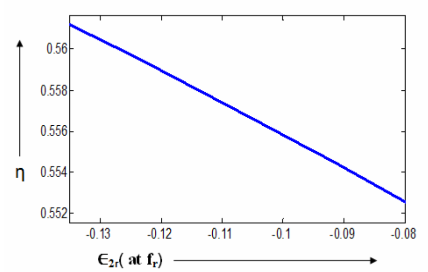
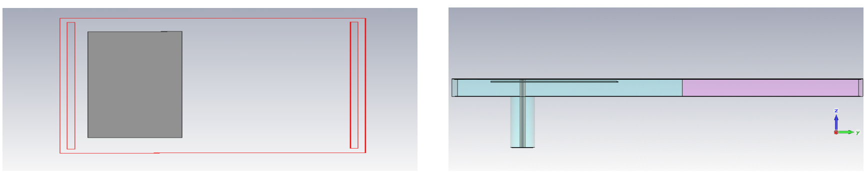


Figure 5. The possible choices of filling ratio and corresponding permittivity of the NG metamaterial (at $f = f_r$).

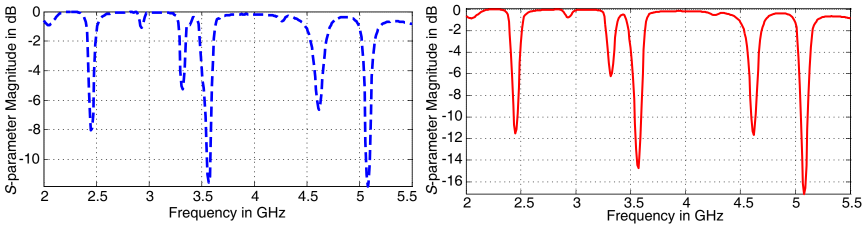


(a) (b)

Figure 6. Proposed 40 mm × 35 mm ENG metamaterial loaded microstrip patch antenna with symmetrical slots and parasitic patch. (a) Top view. (b) Side view. Design parameters: $L_p = 40\,\text{mm}$, $W_p = 35\,\text{mm}$, $L_g = 75\,\text{mm}$, $W_g = 75\,\text{mm}$, $f_p = 15.6373\,\text{mm}$, $h = 1.7\,\text{mm}$, $\eta = 0.5576$, $\varepsilon_{1r} = 2.2$, $\mu_{1r} = 1$, $\mu_{2r} = 1$ and $\varepsilon_{2r}\,(\text{at} f_r) = -0.1111$ in case of ENG loading, f_r = chosen resonant frequency = 4.7 GHz. Parasitic patch dimension: 28.66 mm (parallel to slots or x-axis) ×14.32 mm × 0.1 mm. Distance between main and parasitic patch: 0.2 mm. Dimension of both slots: 33 mm × 1 m.

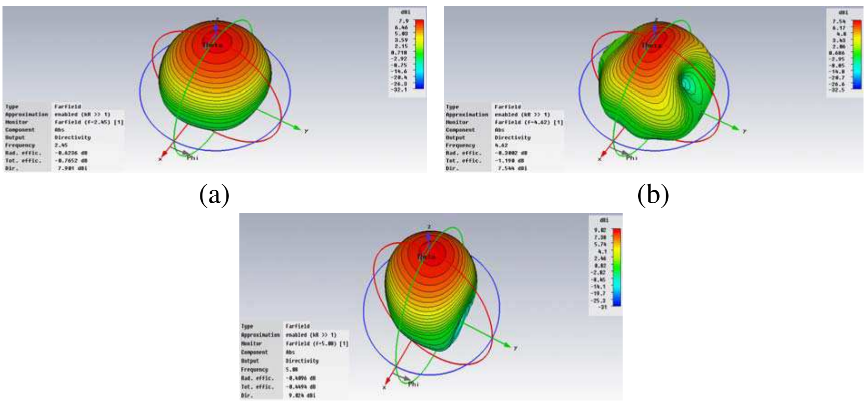
loaded with DPS-metamaterial juxtaposed layer (because of broadside null radiation problem).

To solve the problem of bandwidth enhancement and impedance matching, we have applied the concept of parasitic patch in our current contribution. In our metamaterial loaded antenna, we have solved these problems by using a single parasitic patch underneath the radiating patch (inside the DPS substrate only) (Figure 6). In



(a) (b)

Figure 7. *S*-parameter performance of proposed antenna (Figure 6). (a) Without parasitic patch. (b) With parasitic patch.



(a) (b) (c)

Figure 8. (a) Conventional TM_{010} mode 3-D radiation pattern (at 2.45 GHz) radiation of proposed antenna (Figure 6). (b) Unconventional $TM^1_{0\delta 0}$ mode 3-D pattern (at 4.62 GHz) of proposed antenna (Figure 6). (c) Unconventional $TM^2_{0\delta 0}$ mode 3-D pattern (at 5.08 GHz) of proposed antenna (Figure 6).

this case, the parasitic patch must have larger dimension (28.66 mm) parallel to symmetrical slots (Figure 6). *S*-parameter performance of this antenna with and without parasitic patch is shown in Figure 7.

It is noticeable fact that TM_{030} mode was in 3.63 GHz without metamaterial loading (using normal DPS with symmetric slots in the patch) Figure 3. After the loading of ENG metamaterial, the two modified modes are found at 4.62 GHz and 5.08 GHz. Both modes are quite far from 3.63 GHz which was found from DPS substrate only (using two symmetric slots in both the cases). We are tagging these modes as $TM^1_{0\delta 0}$ mode and $TM^2_{0\delta 0}$ mode. Perhaps such a successful triple band rectangular patch antenna is proposed for the first time here whose directivity performance is more than satisfactory. The directivities at 2.45 GHz, 4.62 GHz and 5.08 GHz are 7.901 dBi, 7.544 dBi and 9.024 dBi respectively Figures 8(a)–(c).

According to Maci et al. frequency ratio found is $f_H/f_L = 1.5$ to maximum 1.6 using dual symmetrical slots. But in our proposed antenna, the frequency ratios are $f_2/f_1 = 1.886$ and $f_3/f_1 = 2.073$. It is to be mentioned that in case of designing triple band antenna like this using MNG metamaterial, directivity of TM_{010} may deteriorate significantly. In addition, we find another band which is at 3.57 GHz shows very poor radiation efficiency. Otherwise the antenna could be used as tetra-band antenna.

4. PHYSICAL INSIGHT ON NEW OBSERVATION

Newly introduced $TM^1_{0\delta0}$ and $TM^2_{0\delta0}$ (in both cases $3 < \delta < 4$) modes may cause confusion and require rigorous explanation. Actually, we expected only one modified 'interface resonance' mode near 4.7 GHz (as the MNG metamaterial loaded antennas of [5]). But in this ENG metamaterial loaded antenna, $k_1\eta L$ was chosen above 180° ($k_1\eta L = 187°$). So, $k_1\eta L$ must pass 180° before reaching to 187°. Frequency required to maintain 180° phase shift (For conventional better radiation performance as TM_{010} is around 4.62 GHz and also there is a resonance present on that frequency. Consequently, a modified mode is found on that frequency and satisfactory radiation performance is obtained. Although only one resonant state (with modified or satisfactory radiation pattern) was predicted, surprisingly, we have achieved two modified 'interface resonance' modes. We have used $f_0 = 3.6$ GHz in our design. As a result, ϵ_{eff} is very high at 3.57 GHz causing drastic increase in Q factor of the antenna. As a result, radiation efficiency is significantly reduced (Figure 9) which is about 13% only (−8.868 dBi). So, this band is not operational in practical application. In this circumstances, we are expecting to introduce tetra band if radiation performance of TM_{030} (3.57 GHz)

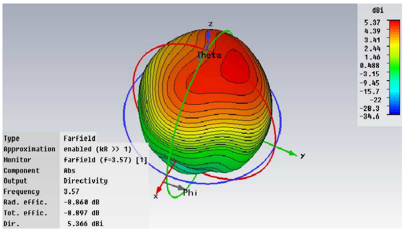


Figure 9. Dissatisfactory radiation performance at 3.57 GHz.

mode can be improved with proper optimization of parameters in near future. Still a question remains on the use of parasitic patch for bandwidth enhancement of all the bands. According to [1], ENG metamaterial was modeled as a positive inductive (or negative capacitance) element in case of TM mode propagation. Moreover, the reason behind the narrow bandwidth (and poor impedance matching) of rectangular patch antenna is the inductive effect of coaxial feed and symmetrical slots. ENG loading in this antenna increases inductive effect drastically. As a result, much poor impedance matching has been found (Figure 7(a)). Our primary target was to introduce capacitive effect to neutralize reactive part of input impedance and eventually to increase the bandwidth by proper impedance matching. For this reason, parasitic patch has been used here. But according to our insight, bandwidth enhancement of MNG metamaterial loaded antenna cannot be achieved with parasitic patch concept as this ENG metamaterial loaded antenna. Full wave analysis based [10] realistic simulated results in these specific cases (ENG and MNG metamaterial) have validated our prediction of using parasitic patch.

5. CONCLUSION

In this paper, we have proposed a complete new design procedure for novel triple band rectangular patch antenna loaded with metamaterial. As per we know, in literature, such a triple band antenna is unavailable. Moreover, the directivity and radiation efficiency performance of such an antenna is more than impressive. Besides, we have also shown an effective way to enhance the bandwidth of such metamaterial loaded patch antennas. The results that we have reported in this paper are found by full wave analysis based realistic simulations (considering dispersive and lossy metamaterial, feed loss and so on). That is why we believe that the proposed designs and techniques will be very promising for real life implementation.

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