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A unique metamaterial inspired star-slot UWB antenna with soft surface ground

Hassan Umair\textsuperscript{a}, M. Jasim Uddin\textsuperscript{b}, M. Habib Ullah\textsuperscript{a}, Tarik Bin Abdul Latef\textsuperscript{a}, Wan nor Liza Binti Wan Mahadi\textsuperscript{a}, and Mohamadariff Bin Othman\textsuperscript{a}

\textsuperscript{a}Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia; \textsuperscript{b}School of Electrical Engineering and Computer Science, Queensland University of Technology, Brisbane, Australia

ABSTRACT
A metamaterial (MTM) inspired star-slot planar microstrip line fed ultra-wideband (UWB) antenna having a soft-surface ground structure is presented in this paper. The proposed antenna comprises periodically repeated star-slot unit cells on patch (radiating) side. This feature helps achieve an UWB from 4.0 to 16.2 GHz. Back lobe radiation is suppressed when the ground metallic part is partially replaced by periodic square-shaped cross-slot soft-surface unit cells. The dispersion relation exhibits a wide bandgap in the resonance frequency regions. The backward wave displays a balanced condition when series and shunt frequencies are equivalent ($\omega_{se} = \omega_{sh}$), whereas it displays an unbalanced condition when they are not ($\omega_{se} \neq \omega_{sh}$). The periodic star rings etched on the metal patch enhance bore sight gain to a maximum of 8 dBi at 9.2 GHz. The antenna is fabricated on a Duroid substrate with overall dimensions of $27.00 \times 31.40 \times 1.57$ mm$^3$ with a 10.0 GHz of the resonant frequency. The numerical and experimental results verify the proposed artificial metamaterial design structure that matches the theory.

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KEYWORDS
Metamaterial; microstrip antenna; ultra-wide band (UWB); soft surface ground; back radiation reduction

Introduction

In recent years, microstrip antennas have been widely used in the radio frequency (RF) front end and satisfy stringent requirements owing to their advantages such as light weight, low profile, unidirectional radiation, good integration, stable gain, and impedance bandwidth, and ease of fabrication (Pyo et al. 2010; Sajuyigbe et al. 2010; Sánchez-Fernández et al. 2010; Zhang et al. 2009). However, it is commonly a challenge to build them with high permittivity substrates, with wider bandwidth and least radiation pattern degradation, enhanced radiation efficiency, appropriate impedance matching, and high integration level with active components (Uddin and Ullah 2016; Ullah et al. 2015).

Utilizing various techniques to achieve ultra-wide bandwidth are quite researched in literature; however, the attainment of enhanced radiation properties along with wide bandwidth has been quite a daunting task. For example, offsetting the input microstrip feed line to patch antenna lying on a partial ground plane achieves wide bandwidth from 2.96 to 19 GHz; however, the average gain achieved over the wide bandwidth remains on the lower side with a value of 4.59 dBi (Azim et al. 2016). Similarly in (Siddique, Azim,
and Islam (2019), the authors achieve ultra-wide band with two-band notches by utilizing a pair of resonators in the vicinity of a slotted partial ground plane under the patch radiator. The design is compact in size but the achieved average gain still suffers and remains below 4 dBi. Therefore, designing patch antennas with wide bandwidth and improved radiation properties is still an open area for researchers.

Using microstrip antennas fed on plasma surface waves is a great opportunity to reduce side lobes, which can enhance radiation patterns. In the literature, a number of plasma surface structures have been investigated, including mushroom structure as surface-wave suppression electromagnetic band-gap (EBG) structures (Coulombe, Koodiani, and Caloz 2010; Yang and Rahmat-Samii 2003a). They utilize mushroom-like metallic patches shorted with the ground plane by making plated through-hole vias as a technique to suppress surface waves. The corresponding milling process, however, is difficult and expensive. In (Coccioli et al. 1999; Gonzalo, De Maagt, and Sorolla 1999; Sharma and Shafai 2001; Sigalas, Biswas, and Ho 1996), a unipolar compact photonic bandgap (UC-PBG) surface is used to reduce surface-wave loss; the technique is suitable to enhance a broadside gain. However, UC-PBG surface waves are effectively suppressed when a thick substrate is utilized. In (Lee et al. 2005; Leger, Monediere, and Jecko 2005), the EBG structure employs the frequency selective surface (FSS) to enhance the directivity of microstrip antennas. Nevertheless, this technique requires a wider dimension area.

In view of the above, metamaterial-based antennas may provide an overall good performance by inserting periodic unit cells on patch surface, while keeping the size of these unit cells much smaller compared to the wavelength (Lim, Caloz, and Itoh 2004; Zhu and Eleftheriades 2008). The surface wave suppression on the metamaterial antenna reduces side lobes leading to better radiation patterns, gain enhancement, and improvement of bandwidth.

Here we propose a metamaterial-based UWB microstrip antenna, where the radiating patch on the substrate comprises a periodic pattern of star-slot structure, and underneath the substrate is the partial ground plane with remaining area covered by periodic square-shaped cross-slot unit cells (soft surface). The radiating patch surface enhances the bandwidth of the antenna as well as impacts the broadside gain. The artificial ground structure (soft surface) suppresses the surface-wave radiation, thereby enhances the antenna efficiency and broadside gain by reducing the back radiation. The proposed design is based on sub-lambda structures as the dimensions are electrically small in the entire frequency bandwidth. It is typically less than or equal to one-tenth of the guided wavelength (long-wavelength regime). The experimental results confirm the enriched broadside gain and directivity compared to the original (full) and partial ground antenna.

### Antenna design and parametric analysis

#### Antenna design

To simplify the design configuration, we consider a microstrip rectangular patch on a substrate; the substrate has thickness $t$ and dielectric constant $\varepsilon_r$. The rectangular patch is fed with a microstrip line connected to the SMA connector matching the 50 Ω impedance. To
achieve the left-handed (LH) pattern, we design an artificial periodic structure. The detailed structure and its geometrical configuration are shown in Figure 1a. The antenna is fabricated on a Duroid substrate with $t = 62$ mils, $\varepsilon_r = 2.2$, and has a compact size of $31.4 \times 27.0$ mm$^2$. The radiating patch consists of periodically repeated star-shape slots as unit cells, whereas the ground plane consists of a square-shaped cross-slots structure. Both the radiating patch and the ground plane correspond to the inductive-capacitive coupling equivalent circuit that can be determined by the left-handed metamaterial structure. The microstrip radiating patch has a size of $16 \times 12$ mm$^2$, where $5 \times 7$ unit cells are arranged periodically. The ground plane has a size of $30.4 \times 27.0$ mm$^2$ with $7 \times 6$ square cross-shaped unit cell structure (soft surface) configuration. The physical property pertaining to coupling characteristics between upper and lower layers based on equivalent lumped model is explained in the next section. The LH microstrip patch is mounted on the substrate to enhance the radiation pattern and to achieve a wider bandwidth. Figure 1a also shows the ground configuration of the proposed antenna exhibiting symmetrical periodic square cross-slot cut soft-surface ground plane. As shown in Figure 1b, the metallic partial ground plane underneath the antenna is of approximately one-fourth of the length of the ground plane, i.e., $l = 7.7$ mm. The rest of the ground part is covered with an effective cross-slot soft surface in order to improve the radiation pattern (Ullah and Islam 2014). To obtain the optimum results, the proposed antenna parameters are compared with partial ground plane antenna and the original antenna structure (full ground plane). The configuration of the microstrip patch represents the LH behavior whereas the ground soft surface represents the composite right-left-handed (CRLH) transmission line structure. The original microstrip patch exhibits narrow resonance; however, the microstrip patch along with the metamaterial unit cell and soft-surface ground represents the widest bandgap in
comparison to full and partial grounds. Figure 2 compares the performance of full, partial, and metamaterial ground structures.

**Equivalent circuit model**

Here we discuss the equivalent circuit model of the proposed antenna. Although the design of the proposed structure is based primarily on the parametric study, the objective of highlighting the equivalent circuit is to give a better understanding of the underlying operation principle of the proposed antenna. The equivalent circuit model of the proposed metamaterial antenna configuration considering one-dimension is shown in Figure 3. The microstrip patch inductive-capacitive configuration is connected to the coupling slot (Lo, Solomon, and Richards 1979). The ground plane soft-surface structure model employs single-unit cells, creating capacitive coupling outside of the patch area. During antenna excitation, the wave is coupled between the soft surface and the patch areas and is radiated.
back toward the upper plane (Sze and Wong 2001). This effect is caused by the radiation resistance represented by the lumped component ($R_p$). The equivalent circuit model can be categorized into three parts: patch resonance, coupling slot, and soft surface. The LH and RH transmission line can be characterized by a series of resonance employing ($\frac{L_R}{2}, 2C_L$) and shunt resonance using ($C_L, L_R$), to represent the soft-surface ground. The microstrip patch constructs only LH transmission line ($R_p, L_p$, and $C_p$). The coupling between the patch and the soft surface determines the coupling slot $C_C$.

**Effect of microstrip patch with finite unit cells**

The geometry and configuration of the microstrip patch consisting of periodic unit cells and its microstrip feed are shown in Figure 1. The unit cell is designed using star-shaped rings with a tiny split, etched on the substrate, and a microstrip line feed connecting the patch to the SMA connector. The goal of the proposed antenna design is to create a backward wave which can radiate and at the same time produce a high resonance. To achieve this goal, we optimize the unit cell with a special unit cell shape. The proposed star-slot tiny unit cells are less than the wavelength ($\lambda/4$) which corresponds to the rule of left-handed (LH) materials known as metamaterials. This specific unit cell produces capacitance and inductance, and therefore, the combination of unit cells creates a series capacitance and shunt inductance. When this series capacitance and shunt inductance is large enough, the structure gives a backward wave (LH) behavior. On the other hand, bottom ground plane unit cells also help improve the resonance. The gap between unit cells increases the radiation and creates wide bandwidth. Figure 4 shows the comparison of numerical results of $S_{11}$ where $5 \times 7$ unit-cell configuration on the patch side exhibits the best performance achieving a wide band gap in 4–16.2 GHz frequency band. To investigate the transmitted power performance in the direction of peak radiation, Figure 5 shows the parametric gain performance for three unit cell configurations of the patch structure. It shows the gain for $5 \times 3$, $5 \times 5$ and $5 \times 7$ unit cell configurations of patch loaded with star-slot unit cell structure. For the optimum dimensions ($5 \times 7$), the average

![Figure 4](image_url)
gain is found to be 7 dB and peak gain is 8 dBi at 9.2 GHz frequency. This increase in gain is achieved because of the following. On the upper patch, the periodic gaps are designed in the form of isolated micro-star-slot shapes while on the bottom-ground plane, periodically distributed square-shaped cross-slot gaps are designed. To maintain the transmission consistency of input energy, the metal in and around the feed line area is, however, not etched. Each unit cell gap is of 0.5 mm on the ground plane and therefore different inductance components are obtained which produce strong resonance, gain, and bandwidth. In order to optimize the results, the upper patch and bottom plane are coupled to form a capacitive-inductive (C-L) equivalent circuit. Therefore, the radiation changes to a backward wave which travels along the plane of the patch. The designed antenna’s parametric analysis shows that 0.5-mm gaps of patch and bottom plane fall in 8.5 GHz and 14.5 GHz wide band-gap areas (4 to 16.2 GHz bandwidth). In order to achieve a high and wide capacitive coupling resonance, patch unit cells on top of the soft-surface ground plane are increased. It is realized that a strong resonance occurs from 5 × 7 unit cell patch with 7 × 6 periodic square cross-slots underneath. The numerical results verify the periodic artificial LH structure on the patch antenna that can attain the increased gain.

**Effect of finite soft-surface ground**

A flat material is commonly used as a reflector or ground plane that creates almost one half of the radiation in the boresight direction and improves the antenna’s gain (Li et al. 2005; Yang and Rahmat-Samii 2003b). However, poor radiation efficiency may be experienced when the material is excited due to the image current cancellation. This effect can be observed in a quarter-wavelength space between the radiating element and the ground plane. The metallic charge induced conducting currents circulate on the surface and radiate efficiently into the surrounding space. In addition, the soft surface reflects the electromagnetic waves without phase reversal, behaving like an artificial magnetic conductor. The propagation waves can be excited between conducting surfaces and the space in between. The effective dielectric constant of a soft-material surface can be expressed as

![Figure 5. Performance comparison of antenna gain for several unit cell configurations: 5 × 7 with 16.0-mm patch length, 5 × 5-mm unit cell with 12.9-mm patch length and 5 × 3 with 6.7-mm patch length.](image-url)
\[ \varepsilon = 1 - \frac{j\sigma}{\omega \varepsilon_0} \]  

(1)

where \( \sigma \) is the conductivity of the material, \( \varepsilon_0 \) is free space permittivity and \( \omega \) is angular frequency. The conductivity can be expressed as

\[ \sigma = \frac{nq^2 \tau}{1 + j\omega \tau} \]  

(2)

where \( \tau \) is the electron collision time, \( q \) is the electron charge, \( m \) is the effective electron mass, and \( n \) is the density. We also determine the soft-surface penetration depth (\( \gamma \)) into the metal using the following expression:

\[ \gamma = (1 + j) \sqrt{\frac{\omega \mu_0 \sigma}{2}} = \frac{(1 + j)}{\delta} \]  

(3)

where \( \mu_0 \) is free space permeability and \( \delta \) is skin depth. Figure 1a illustrates the soft-surface ground plane with finite periodic compact unit cells. To investigate the effects of soft surface and its characteristics, a parametric comparison of S11 is shown in Figure 6. In this case, several unit cell configurations of the soft surface are presented, while keeping the other dimensional parameters unchanged. Both 7 \( \times \) 2 and 7 \( \times \) 4 unit cell configurations (blue dots and red dashes, respectively) display less rejection than the 7 \( \times \) 6 unit cell configuration, which displays a wide band, 4–16.2 GHz, and appears to be the best suited unit cell configuration for the antenna’s ground plane.

![Figure 6](image_url)

**Figure 6.** Parametric analysis of square cross-slot unit cell configurations of 7 \( \times \) 6, 7 \( \times \) 4, and 7 \( \times \) 2 for antenna’s ground plane.
A critical observation of the antenna’s input impedance is required to achieve port impedance matching as it usually varies with the parameters of the input transmission line. Poor matching means input power will be reflected from the antenna’s input interface and low power will be delivered (radiated) to (from) the antenna. The designed input transmission line feeding the patch comprising periodic start-slot unit cells and lying over a soft-surface ground plane reduces the mismatches to a minimum, and thus the antenna performs over a wide frequency band. The antenna’s input impedance provides near 50-Ω resistance within the band gap frequency. The input impedance values of several unit cell configurations of ground plane over various in-band frequency points are detailed in Table 1.

**Left-handed metamaterial behavior**

In order to verify the metamaterial behavior, it is characterized by the left-handed (LH) and right-handed (RH) property. Excited unit cells with periodic boundaries can have wave propagation in Eigen frequency modes. Figure 7 shows two of them (red and black) against the wave dispersion ($\beta$) that depends on $p/\pi$, where $p$ is the periodicity of one unit cell.

The preliminary resonant mode appears from 3.8 to 4.0 GHz. It specifies that the array lies within the range in the LH medium owing to the negative gradient of the dispersion, where the phase velocity is in the opposite direction to the group velocity (Booket et al. 2012; Zhu and Eleftheriades 2008). In contrast, another resonant mode appears from 15.8 to 16.2 GHz in the RH mode. In this case, phase velocity and group

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$Z_{in} = R + jX$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Surface</td>
<td>6.35</td>
</tr>
<tr>
<td>Partial</td>
<td>7.67</td>
</tr>
<tr>
<td>4 Rows Unit Cells</td>
<td>10.065</td>
</tr>
<tr>
<td>3 Rows Unit Cells</td>
<td>9.478</td>
</tr>
<tr>
<td>2 Rows Unit Cells</td>
<td>10.391</td>
</tr>
<tr>
<td>1 Row Unit Cells</td>
<td>10.34</td>
</tr>
</tbody>
</table>

Figure 7. $\omega$-$\beta$ dispersion diagram curve of a right-handed and left-handed transmission line for balanced and unbalanced case (red and black, respectively). A wide bandgap or attenuation is represented during the unbalanced case ($\omega_{se} \neq \omega_{sh}$). The right-handed transmission line and left-handed transmission line start from the center frequency during the balanced case ($\omega_{se} = \omega_{sh}$).
velocity propagate in the same direction. This wave excitation mode is valid in the unbalanced case only. The unbalanced case specifies that the series resonant frequency is not equivalent to the shunt resonant frequency $(\omega_{se} \neq \omega_{sh})$. Similarly, the balanced case identifies that the series and shunt resonant frequencies are equal $(\omega_{se} = \omega_{sh})$. The graph also shows the attenuation or a stop-band gap (blue dashes) from 4 to 16.2 GHz, separated between two resonant modes. The other wave propagation excitation (red) specifies two modes in LH and RH medium. However, both resonant modes are starting at the same frequency point and no band-gap appears in this region.

**Results and discussion**

Based on unit cell configuration analysis given in the previous section, finalized patch side unit cells configuration is $5 \times 7$ and the ground side unit cell configuration is $7 \times 6$. The designed antenna was fabricated using standard PCB etching technique and has been tested experimentally. The two insets in Figure 8 show the fabricated antenna’s top and bottom sides. The antenna was attached to a VNA to measure its S11 response and Figure 8 also gives a comparison between experimental and simulated S11 results. As seen from the plot, there is a high degree of correlation between the two results and this verifies our simulated model. The achieved wide bandgap ranges from 4 to 16.2 GHz.

We also measured the radiation pattern realized by the MTM antenna. The measured peak gain is 8 dBi at 9.2 GHz. Figure 9 shows the measured radiation patterns of the proposed antenna over various frequencies where field patterns have been compared between the soft-surface ground plane, i.e., with the MTM ground and with original (full) ground, i.e., without the metamaterial ground.

Without the MTM ground, the radiation pattern extends toward the back side in the form of a back lobe, due to surface wave diffraction. With the MTM ground, the back lobe suppresses significantly and the radiation reflects toward the upper area, leading to

**Figure 8.** Simulated vs. measured $S_{11}$ response. Top inset: antenna’s radiating side. Bottom inset: antenna’s ground side.
enhanced directivity and broadside gain. The back lobe suppression effect of the MTM antenna is illustrated in the radiation patterns at 9.1, 15.0, 16.0 GHz. It exhibits that the suppression of back lobe takes place in the region at $\theta = 180^\circ$ with respect to the peak radiation level at $\theta = 0^\circ$, for all frequencies increasing the ratio of front lobe to back lobe. Backward radiation suppression in the region from 90° to 270° occurs because of the utilization of soft-surface ground plane-based metamaterial.

A comparison of the proposed antenna with several antennas from literature is given in Table 2. The proposed antenna has a relatively higher bandwidth.

### Table 2. Comparison of several antennas and their performances.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{min}}$ [GHz]</td>
<td>4</td>
<td>5.7</td>
<td>3</td>
<td>3.85</td>
<td>4.8</td>
</tr>
<tr>
<td>$f_{\text{max}}$ [GHz]</td>
<td>16</td>
<td>8.6</td>
<td>14</td>
<td>15.62</td>
<td>13.4</td>
</tr>
<tr>
<td>$f_{\text{max}}/f_{\text{min}}$</td>
<td>4.1</td>
<td>1.5:1</td>
<td>4.6:1</td>
<td>4.1</td>
<td>2.8:1</td>
</tr>
<tr>
<td>Center frequency</td>
<td>10</td>
<td>7.15</td>
<td>8.5</td>
<td>9.73</td>
<td>9.1</td>
</tr>
<tr>
<td>Bandwidth (BW) [mm]</td>
<td>12</td>
<td>2.9</td>
<td>11</td>
<td>11.7</td>
<td>8.6</td>
</tr>
<tr>
<td>Width ($W$) [mm]</td>
<td>27</td>
<td>28</td>
<td>27.6</td>
<td>27.6</td>
<td>25</td>
</tr>
<tr>
<td>Length ($L$) [mm]</td>
<td>30.4</td>
<td>32</td>
<td>30.8</td>
<td>31.8</td>
<td>25</td>
</tr>
<tr>
<td>$W/\lambda_{\text{min}}$ [mm$^2$]</td>
<td>0.9</td>
<td>0.47</td>
<td>0.78</td>
<td>1.08</td>
<td>0.75</td>
</tr>
<tr>
<td>$L/\lambda_{\text{min}}$ [mm$^2$]</td>
<td>1.0</td>
<td>0.53</td>
<td>0.87</td>
<td>1.24</td>
<td>0.75</td>
</tr>
<tr>
<td>Area [mm$^2$]</td>
<td>820.8</td>
<td>896</td>
<td>850</td>
<td>877.6</td>
<td>625</td>
</tr>
<tr>
<td>Area [$\lambda_{\text{min}}$]</td>
<td>0.9</td>
<td>0.25</td>
<td>0.67</td>
<td>1.34</td>
<td>0.56</td>
</tr>
</tbody>
</table>

### Conclusion

In this paper, a new ultra-wide band metamaterial inspired microstrip antenna was successfully designed and tested. The ground plane uses the surface wave to diffract the radiation. Therefore, back radiation is suppressed and the wave gets radiated toward broadside. The periodic star-slot unit cells on the patch improve the bore-sight gain and enhance the frequency band. The antenna is fed by a 50-Ω transmission line connected with an SMA connector. The symmetric radiation pattern with a peak gain of 8 dBi makes the proposed antenna appropriate for UWB applications.

### Funding

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References


