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A Novel FSS for Gain Enhancement of UWB Printed Antennas

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ABSTRACT: *This paper presents a novel compact unilayer frequency selective surface (FSS) to enhance the gain of an Ultra-Wideband (UWB) monopole antenna. The proposed FSS unit cell consists of simple metallic patterns printed on both sides of $14 \times 14 \text{ mm}^2$ FR4 substrate. The proposed FSS has very low transmission co-efficient and linearly decreasing reflection phase over the bandwidth of 9 GHz (3 to 12 GHz), which makes it suitable candidate to provide in-phase reflection for UWB antennas. The gain of the proposed composite antenna is 8.9 dB which is improved by 4 dB relative to the conventional counterpart.*

Keywords: Frequency selective surface, UWB, high gain, FSS reflector, gain enhancement

1. INTRODUCTION

Ultra-wideband (UWB) technology, being low-power and wideband, has found great applications for short range and high speed communications such as Personal Area Networks (PANs), Body Area Networks (BANs), sensor networks, medical imaging, road-safety, search and rescue systems, life-jacket, landmine detection, UWB pulse radars and smart homes [1], to name a few. The very low power spectral density assigned to UWB technology (typically less than -40dBm), where on one side, makes it ideal for short-range communications, on the other side, it needs relatively high gain antennas with very stable radiation characteristics [ref].

Printed antennas, particularly monopole [2] and slot [3], are extensively being used in ultra-wideband electronic devices due to their compact size, low profile, low fabrication cost, and ultra-wide impedance bandwidth. However, these antennas, when mounted near metallic surfaces and electronic objects inside handheld communication devices suffer from severe impedance mismatch. Moreover, these low profile antennas inherently exhibit low gain and poor directivity particularly at lower frequencies [4]. In certain applications where line-of-

sight communication is critical such as microwave medical imaging, see-through-wall radars and under-rubble radars, UWB antennas with high directivity are required. Properly designed Frequency Selective Surfaces (FSSs) can potentially improve the directivity of printed UWB antennas as well as shield the electronics beneath them. FSS decouples the antenna and the nearby metallic surfaces allowing the mounting of planar antenna very close to the metallic surfaces thus increasing overall system compactness. FSSs are periodic structures, which are constructed by the repetition of a pre-designed unit cell. They act as spatial filters and can be designed to permit electromagnetic (EM) waves to pass through them (band pass FSS) or reflect them (band stop FSS) depending on their specific unit cell structure, operating frequency and polarization of the incoming EM wave. FSSs can be designed to have ultra-wide stopband making them suitable to act as reflectors for UWB antennas. In addition, FSSs can control the phase of the reflected wave to ensure constructive interference at the antenna-plane through in phase reflection.

Along with the above potential benefits, large size and narrow bandwidth are the two main limitations of frequency selective surfaces. Being periodic in nature, it is not easy to realize a compact FSS with single substrate layer exhibiting ultra-wideband characteristics [5]. However, ultra-wideband response can be easily achieved through multilayer FSSs but at the cost of increase in the overall volume and size.

In recent literature, several multi-layer as well as single-layer FSS designs for UWB applications are presented [4-10]. A two-layer FSS with unit cell consisting of a modified cross-loop is presented in [7]. It provides bandwidth of 122% (3–14 GHz) and gain-enhancement of around 4dB, the main disadvantage of this design is its large unit cell size ($17 \times 17 \text{ mm}^2$) and increased overall volume of the multi-layer structure. A two-layer and a four layer FSS structures are presented in [8] and [9] respectively. Though, these multilayer FSSs provide ultrawideband response, yet their practical application in modern communication devices is limited due to their increased size and bulkiness. To avoid bulky volumes, the FSS must be designed on single substrate layer yet it should exhibit broad frequency response. Moreover, single-layer FSS offers advantage of easy integration inside modern portable electronics and communication devices. In [10], a very large percentage bandwidth of 102% (3.9–11.10 GHz) with a single-layer FSS is achieved; however the lower frequency response is very poor not covering the critical part of UWB band from 3.1-3.9 GHz. In [4], a single layer FSS consisting of crossed-loops is presented. It achieved bandwidth of only 52% (7-11.78 GHz) with unit cell size of $15 \times 15 \text{ mm}^2$.

In this article, the author presents a single-layer FSS with ultra-wide stop band characteristics. The geometry of the unit cell is simple and therefore easy to fabricate. The physical size of the FSS unit cell is $16 \text{ mm} \times 16 \text{ mm}$. Electrical dimensions of the unit cell is $0.14 \lambda \times 0.14 \lambda$, where λ refers to the wavelength of the lowest operating frequency of 3 GHz. Along with compact size and single-layer structure, the proposed FSS exhibits excellent stop band characteristics in the whole UWB band (3-12 GHz). Moreover, as a test case, the designed FSS is applied as a reflector for a monopole UWB antenna. A significant gain improvement of up to 4 dB is achieved.

2. FSS DESIGN

The response of a frequency selective surface entirely depends on the design of its unit cell. The geometry of the proposed FSS unit cell is shown in Fig. 1(a). It is designed on an inexpensive dielectric substrate FR4 with dielectric constant 4.4, thickness 1.57 mm and loss tangent 0.02. The proposed FSS unit cell consists of three metallic strips connecting the two metallic rectangles. The same metallic pattern is printed on both sides of the FR4 substrate as shown in Figure 1(b). Overall physical dimensions of the unit cell are 14 mm $\times$ 14 mm.

Fig. 1. Geometry of FSS unit cell (a) Front view and (b) side view with dimensions: $L_1 = L_2 = 4.5$ and $L_3 = 6$. Units are in mm.

Fig. 2. Evolution of FSS unit cell (a) Conventional loop structure (b) Conventional loop structure with wide slot (c) Modified loop structure (d) Modified loop structure with offset strips

Design stages of the proposed FSS and their corresponding simulated $|S_{21}|$ results are shown in Fig. 2 and Fig. 3 respectively. The unit cell designed in 1st stage (Fig. 2(a)) is based on conventional loop structure (CLS). The size of CLS is 14 mm $\times$ 14 mm with inner slot having dimensions of 4.5 mm $\times$ 4.5 mm. The response of this CLS printed on both sides of the substrate is shown in Fig. 3. A bandwidth of 8.58 GHz from 4.42-13 GHz with $S_{21} < -10$ dB is achieved. The stopband response of CLS is poor in the lower part of UWB spectrum from 3-4 GHz.

Fig. 3. Simulated transmission coefficient magnitude (S_{21}) of the FSSs shown in Fig. 2.

The first resonance and overall bandwidth of CLS depends on the total size of the unit cell and the width (w) of the inner slot. Large size of both the unit cell and the slot width results in the lower values of the first resonance. Therefore, at the 2nd step shown in Fig. 2(b), the slot-width of CLS is maximally increased ($w=13.1$ mm) to achieve first resonance at lower frequencies. $|S_{21}|$ results in Fig. 3 show that the bandwidth of 3 GHz from 2.2-5.2 GHz is achieved in the lower band. The stopband of this FSS at lower frequencies is good. Contrary to this the stopband bandwidth is badly degraded at higher frequencies, because wider slots limits the bandwidth at higher frequencies.

In 3rd step, a metallic strip at the center of the slot is introduced as shown in Fig. 2 (c). The design of this modified loop structure (MLS) is such that the two smaller loops are formed within the main loop structure (LS). These smaller loops are responsible to broaden the overall frequency response. MSL achieves bandwidth of 7.8 GHz from 2.9-10.7 GHz. To further increase the bandwidth of the unit cell towards higher frequencies, the overall width (w) of the slot is reduced by shifting the outer strips of MLS a little bit inwards as shown in Fig. 2 (d). As expected the lowest operating frequency is shifted a little bit from 2.9 to 3 GHz, however the bandwidth towards the upper end is significantly improved as compared to the MSL. With this design, bandwidth of 9 GHz (3-12 GHz) is achieved.

The reflection phase (S_{11}) is another important performance criterion for the FSSs particularly for the ones to be used in antenna gain enhancement application. The phase of the FSS should linearly decrease to provide in-phase reflection to the antennas [5]. The proposed FSS achieves a linearly decreasing phase from 3-12 GHz (Fig. 4).

To better understand the behavior of the proposed FSS, parametric analysis has been conducted. Distances among the three strips and the length of the strips play a key role in optimizing the stopband. Parameter L_2 , as depicted in Fig. 1, represents the length of the strips. We start the parametric study by varying L_2 while keeping the parameter L_3 constant to 6 mm. Fig. 5 shows the simulated S_{21} magnitude of the FSS with different lengths of L_2 . The transmission band shifts towards the higher side as we increase L_2 . The best stopband at higher frequencies is achieved when L_2 is optimized to 4.5 mm. Further increase in the value L_2 deteriorates this bandwidth.

Fig. 4. Simulated transmission coefficient magnitude (S_{21}) and reflection phase (S_{11}) of the proposed FSS over UWB

Fig. 5. Simulated transmission coefficient magnitude (S_{21}) of the FSS with different values of L_2

Fig. 6. Simulated transmission coefficient magnitude (S_{21}) of the FSS with different values of L_3 .

Fig. 6 shows the simulated S_{21} magnitude of the FSS with different lengths of L_3 when both L_1 and L_2 are set to 4.5 mm. L_3 is the distance between the center strip and outer strips. From Fig. 6, we can see that as L_3 increases (by shifting both the outer strips towards the

ends) from 3.3 mm to 6 mm there is an improvement in the bandwidth particularly at lower frequencies. The bandwidth is the best when L_3 is optimized to 6 mm. When we set L_3 equal to its maximum value of 6.45 mm, the bandwidth deteriorates and the highest operating frequency is reduced to 10.4 GHz.

3. UWB ANTENNA WITH THE FSS

To test the gain enhancing ability of the FSS, a simple UWB monopole antenna is designed. Geometry of the antenna is shown in Fig. 7(a). Tapering of the transmission line and radiating patch is applied to achieve the impedance bandwidth for $VSWR < 2$ over the UWB frequency band.

Fig. 7. (a) Geometry of the proposed UWB monopole antenna. Units are in mm. (b) Configuration of UWB antenna with the proposed FSS view from side and (c) top.

Fig. 7(b) shows the configuration of the UWB antenna with the proposed FSS array. An array of 36 elements (6×6) is constructed by repetition of the unit cell along x -axis and y -axis as shown in Fig. 7(c). The FSS is placed below the antenna so that it can reflect back radiations from the antenna. If, at the antenna plane, the reflected waves by the FSS are in phase with the radiated waves by the antenna then the directivity and front-to-back ratio of the UWB antenna is increased. The phase of the antenna's radiated wave towards FSS increases

with the increase in frequency. The phase of the reflected waves must then decrease with the increase in the frequency to ensure constructive interference at the antenna plane. The simulated reflection phase in Fig. 4, predicts a linearly decreasing reflection phase of the FSS. Hence, the proposed FSS is well-matched to manipulate the phase of the reflected waves, thus ensuring constructive interference at the antenna plane. Height between the FSS and the antenna is an important factor for determining the condition of constructive interference; it is approximated by the following equation:

$$\varphi_{FSS} - 2\beta H = 2n\pi \quad n = \dots - 2, -1, 0, 1 \dots \quad (1)$$

Where, φ_{FSS} is the reflection phase introduced by the FSS, H is the height between the FSS reflector and the antenna and β is the propagation constant in free space. When H is set equal to $\lambda/2$, where λ is the wavelength corresponding to the frequency at which the reflected phase φ_{FSS} is zero, then both sides of Eq. (1) becomes equal. The reflection phase of the FSS crosses zero at 5 GHz. So to satisfy Eq. (1), the value of H is calculated to be 30 mm ($\lambda/2$).

4. FABRICATION AND MEASUREMENTS

The proposed UWB antenna and the FSS array are fabricated on FR4 substrate as shown in Fig 8. Gain of the antenna with FSS reflector is measured with in-house NSI Anechoic Chamber facility. Agilent Technologies E8362B Vector Network Analyzer is used to measure VSWR of the antenna

Fig. 8. Fabricated prototypes. (a) Antenna. (b) FSS. (c) Antenna with FSS.

The measured VSWR of the UWB antenna with and without FSS is shown in Fig. 9. The impedance bandwidth of UWB antenna is 2.8-14.2 GHz. When FSS is placed below the

UWB antenna, there is slight change in its bandwidth due to current changes on the antenna surface caused by reflections from the FSS. Height between the antenna and FSS is optimized to 27 mm (approx. $\lambda/2$ at 5 GHz) to ensure maximum impedance bandwidth for UWB antenna with the FSS. The impedance bandwidth of UWB antenna with the FSS is from 2.7-13.9 GHz showing no significant deterioration in the input impedance of the UWB antenna with the FSS. For comparison, the VSWR for $H=15$ mm is also measured and shown in Fig. 10. In this case the antenna composite bandwidth significantly reduces at lower UWB frequencies concluding that the distance between the antenna and FSS (H) should be selected carefully to satisfy Eq. (1).

Fig. 9. Measured VSWR of the UWB antenna with and without the FSS.

Fig. 10. Peak gain measurements of the UWB antenna with and without the FSS.

The peak gain of UWB monopole antenna without FSS (in free space), as shown in Fig. 10, varies with frequency. The average gain of the antenna is 2.8 dBi. When the FSS is placed below the antenna, the average gain of the antenna is improved to 6.6 dBi. Alternatively, there is gain improvement of 3.8 dBi due to the FSS. Highest gain improvement occurs around 3.1 GHz, where FSS improves antenna gain by 5.7 dBi. The peak gain of 8.9 dBi for the antenna composite is achieved at 7.3 GHz. Application of the FSS greatly improves the gain of the antenna. Fig. 11 shows the measured radiation patterns of the UWB antenna with and without FSS at 3.5 GHz and 7.5 GHz. The antenna has nearly

omnidirectional pattern in xz plane (H -plane) and bidirectional in yz plane (E -plane). The point to be noted is that the radiation patterns become more directional for the FSS backed UWB antenna.

Fig. 11. Measured radiation patterns of the UWB antenna with and without the FSS at (a) 3.5 GHz and (b) 7.5 GHz.

5. CONCLUSION

A novel FSS reflector with compact structure is presented. Electrical dimensions of the unit cell are only $0.14 \lambda \times 0.14 \lambda$, where λ refers to the wavelength corresponding to the lowest operating frequency of 3 GHz, and yet it achieves stopband of 9 GHz from 3-12 GHz. The main advantage of the presented FSS design is that stopband response over the entire UWB band is achieved using single dielectric layer. The gain enhancing ability of the FSS is experimentally demonstrated. Average gain of the presented UWB antenna is improved from 3.8 dBi to 6.6 dBi using the proposed FSS. The highest gain achieved by the antenna composite is 8.9 dBi. The antenna composite is suitable to find application in wireless communication, medical imaging and ground penetrating radar.

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