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Interdigital Coupled Compact FSS Reflector for UWB Antenna Gain Enhancement

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ABSTRACT: A compact UWB FSS reflector is presented based on an interdigital structure for gain enhancement of a UWB antenna. An equivalent circuit approach is proposed for the analysis of the FSS reflector. The reflector comprises a 6×6 array of unit cell dimension $6\,\text{mm} \times 6\,\text{mm}$ and is very compact. The reflector gives a linear phase response over UWB. A UWB monopole antenna is designed with a half circular disc structure based on microstrip technology. A maximum of 4.25 dBi gain enhancement is achieved with this compact FSS reflector when it is placed at a distance below the antenna. The measured results closely follow the simulated ones which proves feasibility of this design.

1. INTRODUCTION

Over the last few years, ultra-wideband (UWB) technology is found to have potential in impulse radio, communication systems, ground-penetrating radar (GPR), and microwave imaging [1]. The commonly used radiator for UWB antenna system is monopole antenna due to its omnidirectional radiation pattern. However, it suffers from low gain and high back side radiation. In order to provide better signal to noise ratio (SNR), the main lobe gain should be much higher than side lobes. The use of frequency selective surface (FSS) reflector is found to be a prominent solution for gain enhancement of monopole antennas. FSS having band-stop response with linear decaying phase over the UWB frequencies is widely used as the reflector of antenna system to minimize back lobe radiation. FSS has found wide space application in radar [2], antenna array [3], and radio frequency identification (RFID) [4].

Multi-layer structures are popular for obtaining UWB frequency response. Stack FSS layers with different frequency responses are a commonly used technology for UWB reflector design [5, 6]. In [6], a UWB FSS reflector based on a four-layer structure improves the gain of a slot antenna over wide band. The use of multiple layers also increases the design cost and complexity and is not suitable for low profile compact antenna system. Therefore, double layer and single layer structures are gaining attention over the years [7]. In [8], a gain enhancement of maximum 7 dB over UWB frequency is obtained with a dual layer FSS which comprises a 5×13 array of unit cell with the dimension of $22.4\,\text{mm} \times 6.5\,\text{mm}$. Recently, metamaterial is used for the design of miniaturized FSS [9]. FSS reflectors based on a single layer structure are found to have potential for gain enhancement in a low-profile compact antenna system [7, 10, 11]. In [12], a stopband characteristic of FSS reflector is obtained with a ring-based structure. A miniaturized FSS is designed with higher dielectric constant material, but it also increases the design cost.

This paper presents a compact FSS reflector based on an interdigital capacitor for gain enhancement of a UWB monopole antenna. The FSS reflector exhibits a linear phase response with band-stop characteristic over UWB frequency.

The unit cell size of FSS is $6\,\text{mm} \times 6\,\text{mm}$, which is $0.06\lambda_L$ (corresponding to the lowest resonant frequency) and hence is compact. A 6×6 array of the unit cell FSS is loaded to a UWB monopole antenna to achieve a gain enhancement of maximum 4.25 dBi as compared to an antenna without loading over the UWB range. The design and theoretical analysis of the proposed work is carried out with CST Microwave Studio. The design is also fabricated, and the measured results are compared with the simulated one to validate the work.

This work is represented as follows. Section 2 discusses the design of unit cell, UWB monopole antenna, the FSS reflector loaded UWB antenna, and their simulation. In Section 3, the prototypes of the proposed design are fabricated and measured, and the test results are compared with the simulated ones. Finally, in Section 4, the conclusions of the proposed work are provided.

2. DESIGN AND RESULTS

The design of the proposed work is carried out in two steps; first a UWB monopole antenna is designed with a simple half circular metallic patch, and then a compact FSS reflector is realized using an interdigital coupled resonator to enhance the antenna performance over the wide band.

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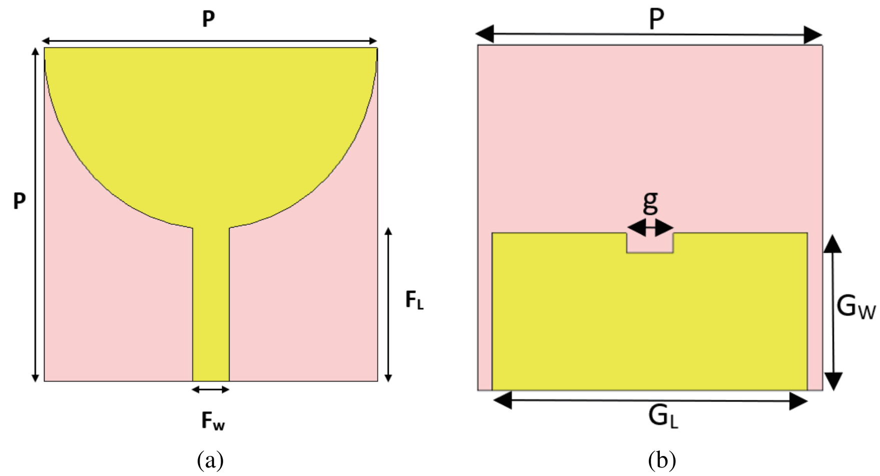


FIGURE 1. Proposed UWB antenna; (a) Top plane, (b) Bottom Plane (Physical Dimension (in 'mm'): P (patch length/width) = 35, F_w (Feed width) = 3.84, F_L (Feed length) = 16.11, g (ground cut) = 4.80, G_L (ground length) = 32, G_w (ground width) = 16).

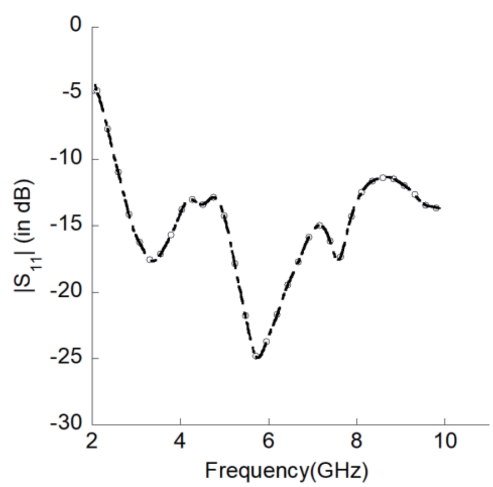


FIGURE 2. Proposed antenna reflection response.

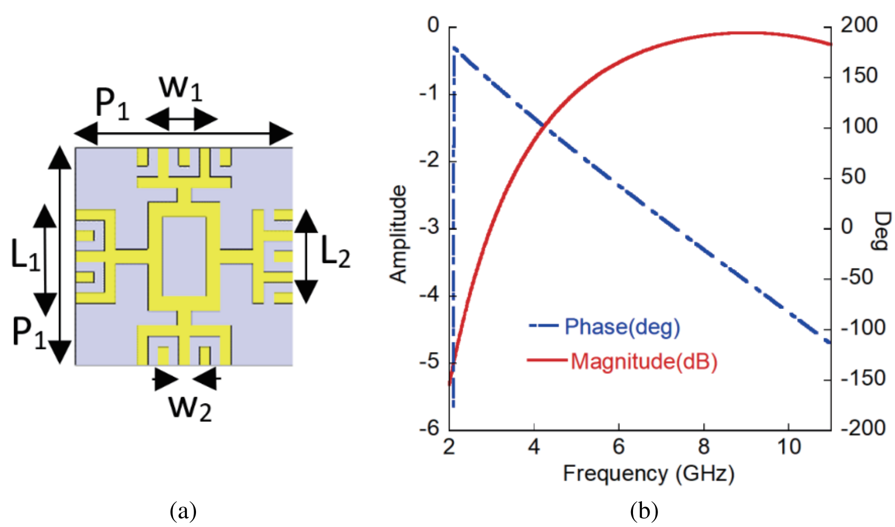


FIGURE 3. Proposed FSS reflector; (a) Unit cell, (b) Reflection Magnitude and phase response (Physical Dimension (in 'mm'): P_1 (periodicity) = 6, W_1 (width of inner ring) = 2, W_2 = 0.3, L_1 = 3, L_2 = 2.6).

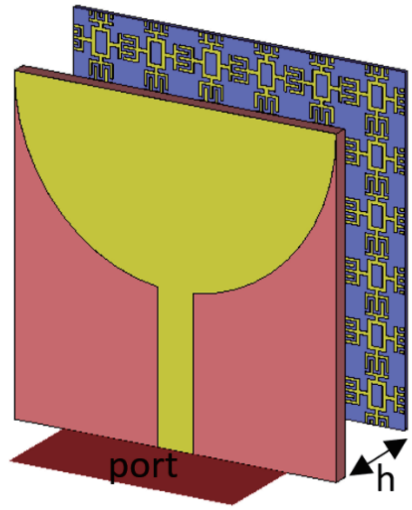


FIGURE 4. Proposed FSS with antenna setup.

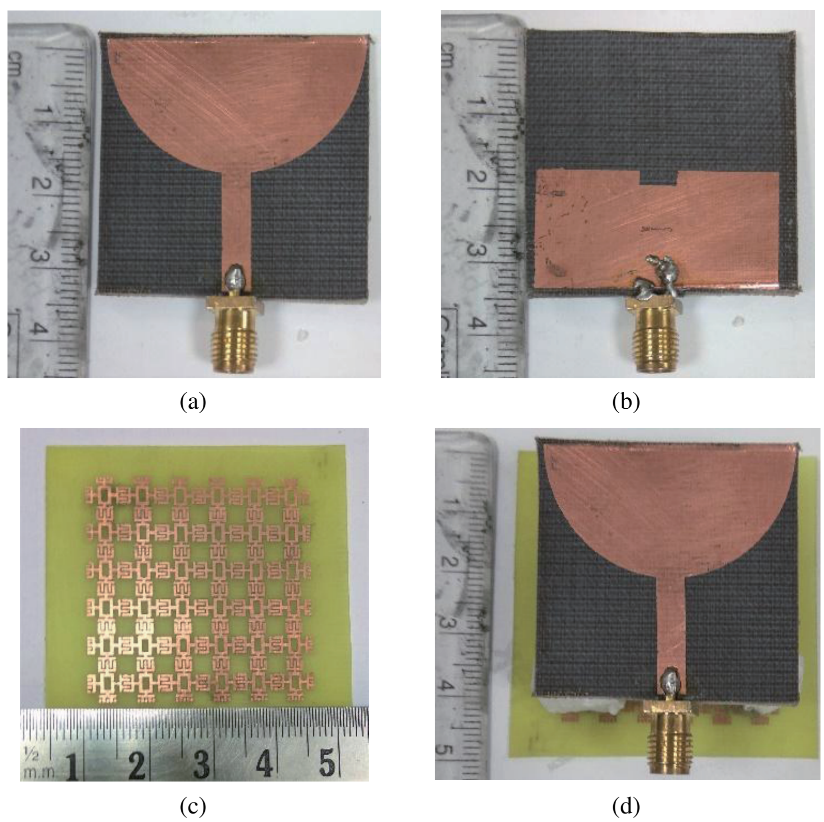


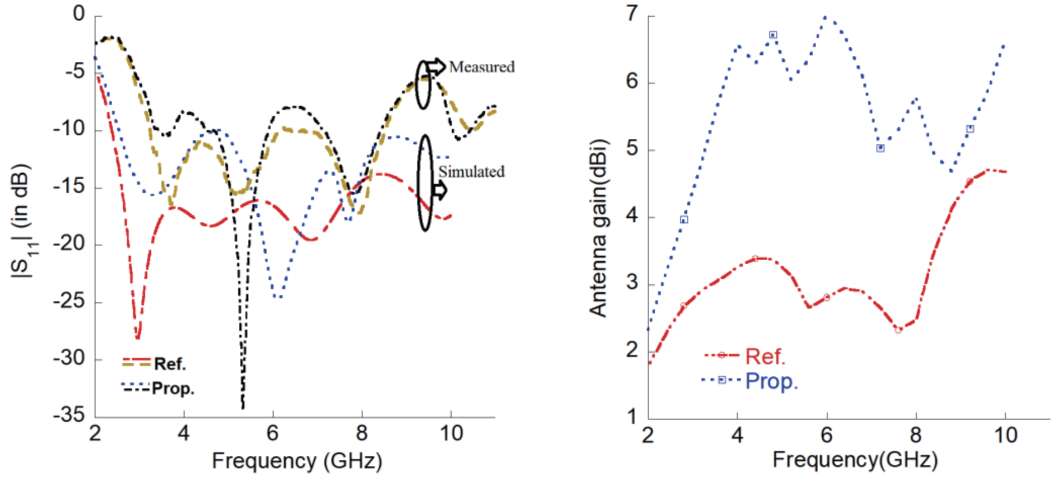
FIGURE 5. Fabricated prototypes: (a) Top plane of antenna. (b) Ground plane of antenna. (c) FSS. (d) Proposed FSS with antenna setup.

2.1. Antenna Design & Results

UWB antenna can be simply realized by a monopole circular disc patch. The motivation of the proposed antenna comes from this but with half circular disc for compact design. The proposed antenna in Fig. 1 is fabricated with a low loss Arlon substrate of permittivity 3.2, loss tangent 0.003, and height 1.6 mm. The ground layer at the back plane is truncated around the feed for impedance matching purpose. Fig. 2 depicts the reflection coefficient below -10 dB from 2.37 GHz to 10.80 GHz with fractional bandwidth of 129%, and hence a good impedance matching over the wideband is achieved.

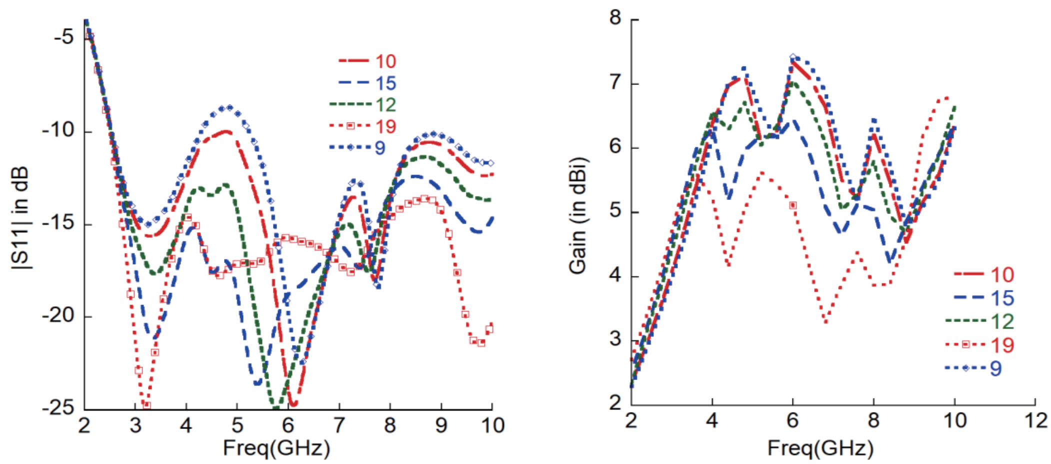
2.2. FSS Design & Results

The proposed FSS comprises a periodic array of unit cell elements having periodicity of 6 mm $\times$ 6 mm in the vertical and horizontal directions. The top metallic layer is a compact interdigital coupled resonator printed on an FR4 dielectric sub-



(a) (b)

FIGURE 6. Proposed FSS with Antenna's. (a) Simulated and measured S_{11}. (b) Gain plot.



(a) (b)

FIGURE 7. Parametric studies with the gap (in mm): (a) $|S_{11}|$, (b) Gain.

strate of permittivity 4.4, loss tangent 0.02, and height 0.5 mm as given in Fig. 3(a).

The magnitude and phase plot of the FSS (in Fig. 3(b)) depicts that it has linear phase response over the antenna operating frequencies, and the reflection coefficient is also maximum. Thus, it is well suited as a reflector for the gain enhancement of the antenna.

2.3. FSS Reflector with Antenna

The FSS reflector with size equal to the antenna is obtained by constituting a 6×6 array of unit cell elements and placed beneath the antenna at a distance h from the substrate and given in Fig. 4. Antenna gain can be enhanced when the EM wave radiated by the antenna and the reflected wave from the FSS are in phase at the antenna interface. Therefore, the following formulae must be satisfied [11].

$$\emptyset\_fss - 2\beta h = 2n\pi, \quad n = -\infty \text{ to } +\infty \tag{1}$$

where $\emptyset\_fss$ is the FSS reflection phase; β is the free space propagation constant. The air gap h is calculated as 12 mm.

Figure 5 shows the fabricated prototype of the proposed design, and its experimental validation is done by comparing with simulated one (in Fig. 6). The measured -10 dB reflection coefficient bandwidths for the ref. and proposed design are 92.80% and 84.74%, respectively. The measured reflection coefficient patterns closely follow the simulated one except that extra losses are added due to fabrication. A maximum gain enhancement of 4.25 dBi is obtained with the FSS reflector when it is placed below the antenna at a distance of 12 mm and given in Fig. 6(b).

The parametric studies on height (h) on the reflection and gain of the proposed antenna is given in Fig. 7. The result shows that with an increase in h, the return loss performance is improved due to loading effect, whereas the gain performance decreases with the increase in h due to the magnitude of reflected signal inversely proportional with the distance between the antenna and reflector.

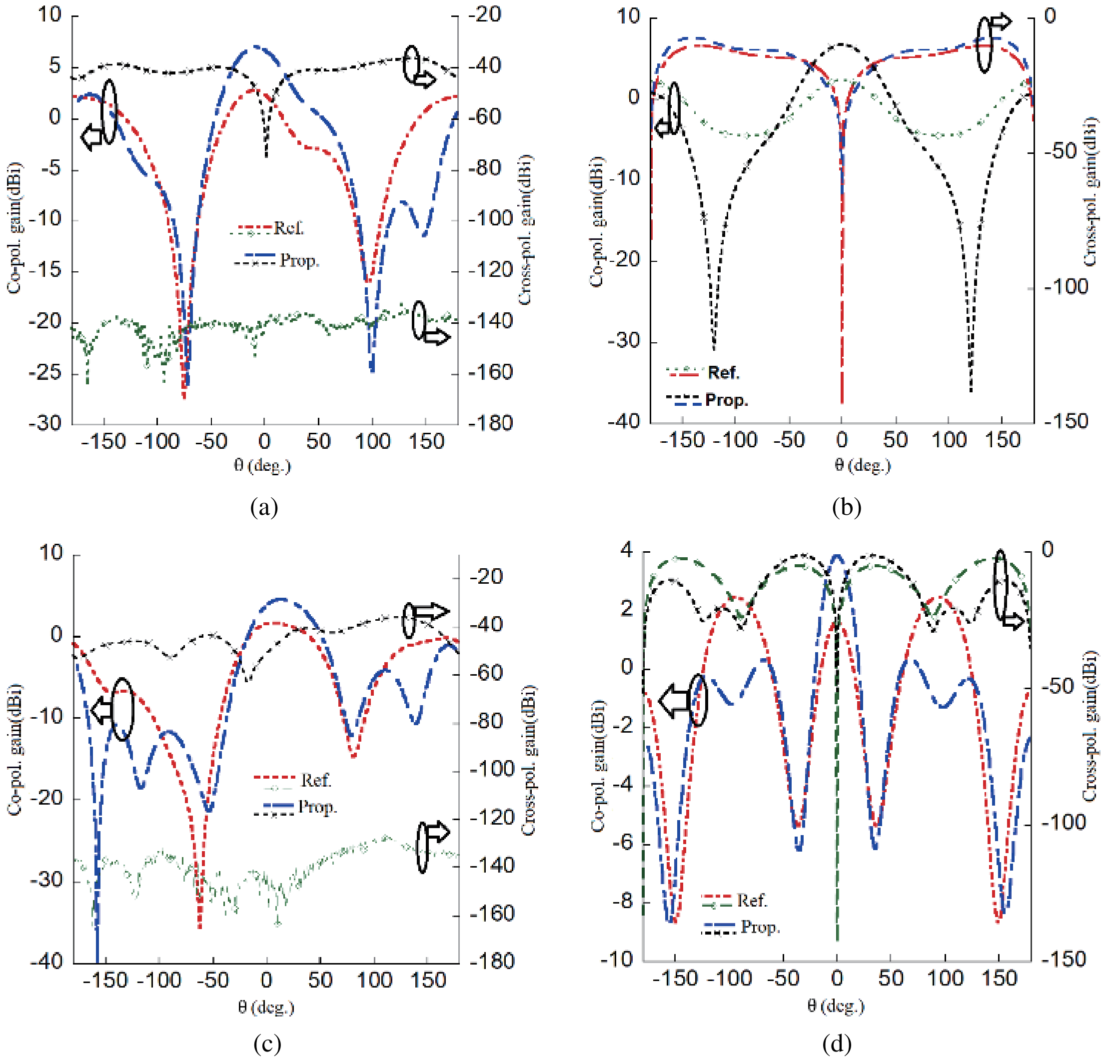


FIGURE 8. Radiation patterns of the Ref. (antenna) and Prop. (antenna with FSS): (a) E-plane, (b) H-plane — 6 GHz, (b) E-plane, (c) H-plane — 8 GHz.

TABLE 1. Comparison Table.

Ref.	Structure dimensions (mm^2)	FSS unit cell size (mm^2)	Bandwidth (GHz)	Max gain enhanced (dBi)
[12]	115 × 115	13.5 × 13.5	3.0–11	4.5
[13]	84 × 84	14 × 14	4.7–14.9	3.5
[14]	33 × 33	11 × 11	3.8–10.6	3.5
[15]	82.5 × 82.5	8.25 × 8.25	2.5–11.0	3.0
This work	36 × 36	6 × 6	2.5–10.8	4.25

Figure 8 illustrates the radiation patterns of the antenna (ref.) and antenna with FSS (prop.) structures on the two orthogonal planes (E and H). The results clearly demonstrate the improvement with loading of FSS reflector to the antenna. The improvement in gain in the main lobe with narrow bandwidth and reduction of back-lobe levels is due to the addition of FSS reflector.

The main parameters of the proposed structure are compared with existing reported designs and tabulated in Table 1. In [12], a UWB FSS reflector with the unit cell dimension of 13.5 × 13.5 mm^2 is proposed to obtain a maximum gain enhancement of 4.5 dBi over the band. But the structure suffers from larger size of 115 × 115 mm^2. A relatively lesser structure dimension with 3.5 dBi gain enhancement is achieved in [13]. In [14], a compact FSS with the unit cell dimension of 11×11 mm^2 is able to enhance the antenna gain over UWB range. A more compact FSS structure is reported in [15] but with larger structure and lesser gain. The proposed work is much compact as compared to others and also has good performances.

3. CONCLUSION

A compact FSS reflector is proposed for gain enhancement of UWB antennas. The design topology is based on an interdigital coupled resonator for a miniaturized structure. The structure is able to give maximum gain enhancement of 4.25 dBi over the UWB frequency when it is placed below a half circular disc radiator. The radiation results clearly demonstrate improvement in gain in the main lobe with narrow bandwidth, and reduction of back-lobe levels is due to the addition of FSS reflector. The experimental results validate the design performance over the UWB frequency. This FSS reflector can be applied to any other antennas with some optimization in the design parameters and hence proves novelty of the structure.

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