Interdigital Coupled Compact FSS Reflector for UWB Antenna Gain Enhancement

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Abstract

A compact UWB FSS reflector is presented based on interdigital structure for gain enhancement of an 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 which is very compact. The reflector gives a linear phase response over UWB band. A UWB monopole antenna is designed with a half circular disc structure based on microstrip technology. A maximum of 5 dBi gain enhancement is achieved with this compact FSS reflector when placed at a distance below the antenna. The measured results closely follow the simulated ones which proves feasibility of this design.

I. 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 their omnidirectional radiation pattern. However, it suffers from low gain and higher back side radiation. In order to provide better signal to noise ratio (SNR), the main lobe gain is to be much higher as compared to side lobes. The use of FSS reflector is found to be 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 reflector of antenna system to minimize back lobe radiation. FSS has found wide space application in radar [2], antenna array [3], and RFID [4].

Multi-layer structures are popular for obtaining UWB frequency response. The use of stack FSS layers with different frequency responses are commonly used technology for UWB reflector design [5–6]. In [6], a UWB FSS reflector based on four-layer structure improves the gain of a slot antenna over the wide band. The use of multiple layers is also enhanced the design cost and complexity and not suitable for low profile compact antenna system. Therefore, the double layer and single layer structure is gaining attention by the researcher over the years [7]. In [8], a gain enhancement of maximum 7 dB over UWB frequency is obtained with a dual layer FSS comprises 5×13 array of unit cell with 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 single layer structure are found to have potential for gain enhancement in a low-profile compact antenna system [7, 10–11]. In [12], a stop band characteristic of FSS reflector is obtained with ring-based structure. 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 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 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 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 Sect. 3, the prototypes of the proposed design are fabricated and measured, and the test results are compared with the simulated ones. Finally, in Sect. 4, the conclusions of the proposed work are carried out.

Ii. Design And Results

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

A) Antenna Design & Results

The UWB antenna can be simply realized by 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 substrate of permittivity 3.2, loss tangent 0.003 and height of 1.6 mm. The ground layer at the back plane is truncated around the feed for impedance matching purpose. Figure 2 depicts the reflection coefficient below -10 dB is from 2.37 GHz to 10.80 GHz with fractional bandwidth of 129% and hence a good impedance matching over the wideband is achieved.

B) FSS Design & Results

The proposed FSS comprises periodic array of unit cell elements having periodicity of 6 mm×6mm in the vertical and horizontal direction. The top metallic layer is a compact interdigital coupled resonator printed on a dielectric substrate of permittivity 4.4, loss tangent 0.02 and height of 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.

C) FSS Reflector with Antenna

The FSS reflector with size equal to the antenna is obtained by constituting 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].

$$\phi_{fss} - 2\beta h = 2n\pi, n = -\infty \text{ to } +\infty \quad (1)$$

Where, ϕ_{fss} is the FSS reflection phase; β is the free space propagation constant. The airgap h is calculated as 12 mm.

Fig.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 bandwidth for the ref. and proposed design are 92.80 % and 84.74 %, respectively. The measured reflection coefficient patterns are closely following the simulated one except extra losses are added due to fabrication. A maximum gain enhancement of 4.25 dBi is obtained with the FSS reflector when placed below the antenna at a distance of 12 mm and given in Fig. 7.

The parametric studies on height (h) on the reflection and gain of the proposed antenna is given in Fig. 8 and Fig. 9, respectively. 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 increase in h due to magnitude of reflected signal inversely proportional with the distance between the antenna and reflector.

Figure 9 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 below. In [12], a UWB FSS reflector with unit cell dimension of $13.5 \times 13.5 \text{ mm}^2$ is proposed to obtain a maximum gain enhancement of 4.5 dBi over the band. But the structure suffers from larger size of $115 \times 115 \text{ mm}^2$. A relatively lesser structure dimension with 3.5 dBi gain enhancement is achieved in [13]. In [14], a compact FSS with unit cell dimension of $11 \times 11 \text{ mm}^2$ is able 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 have good performances.

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

lII. Conclusion

A compact FSS reflector is proposed for gain enhancement of UWB antennas. The design topology is based on interdigital coupled resonator for miniaturized structure. The structure is able to give maximum gain enhancement of 4.25 dBi over the UWB frequency when 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.

Declarations

- **Funding:** None
- **Conflicts of interest/Competing interests:** None
- **Availability of data and material (data transparency):** Not Applicable
- **Code availability (software application or custom code):** Not Applicable

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Figures

Figure 1

Proposed UWB antenna; (a) Top plane, (b) Bottom Plane (Physical Dimension (in 'mm'): $P=35$, $F_w=3.84$, $F_L=16.11$, $g=4.80$, $G_L=32$, $G_W=16$)

Figure 2

Proposed antenna reflection response

Figure 3

Proposed FSS reflector; (a) Unit cell, (b) Magnitude and phase response (Physical Dimension (in 'mm'):
 $P_1=6$, $W_1=2$, $W_2=0.3$, $L_1=3$, $L_2=2.6$)

Figure 4

Proposed antenna reflection response

(a)

(b)

(c)

(d)

Figure 5

Fabricated prototypes: (a) Top plane of antenna, (b) Ground plane of antenna, (c) FSS, (d) Proposed antenna with FSS

Figure 6

Simulated and measured results

Figure 7

Reference and proposed gain

Figure 8

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