Multioctave Frequency Selective Surface Reflector for Ultrawideband Antennas

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***Abstract*—In this letter, we demonstrate the gain enhancement of an ultrawideband (UWB) antenna, achieved using an appropriately designed multioctave dual-layer frequency selective surface (FSS) reflector. The proposed novel FSS reflects effectively in phase over a bandwidth of about 120%. Hence, significant enhancement in antenna gain has been achieved with a low-profile configuration without compromising the impedance bandwidth of the UWB antenna. The proposed FSS reflector has a low transmission coefficient and linearly decreasing phase over an ultra-wide frequency band, which is the key requirement for providing an effectively in-phase reflection at the antenna plane. The composite structure is compact, with a total height of $\lambda/4$, where λ is the free-space wavelength at the lowest operating frequency of 3 GHz. Experimental results show an impedance bandwidth of 122%. The antenna gain is maintained around 7.5 dBi from 3 to 7 GHz. Between 7–14 GHz, the antenna is more directive with a gain of about 9 dBi with $\pm$0.5 dB variation. Experimental measurements confirm the predicted wideband antenna performance and gain enhancement due to the FSS reflector.**

***Index Terms*—Frequency selective surface (FSS), periodic structures, ultrawideband (UWB).**

I. Introduction

With the potential of handling high data transmission rates, accurate positioning, and short pulse transmission, ultrawideband (UWB) systems continually attract the attention of researchers. These systems are developed for a wide range of applications including ground penetrating radar (GPR), high-resolution microwave and biomedical imaging, and short-range wireless communications. Recent FCC authorization for unlicensed use of the spectrum from 3.1 to 10.6 GHz for UWB technology has led to more focused research in this area. Several printed configurations of monopole and slot antennas excited with microstrip-fed monopoles have been demonstrated for use in UWB systems [1]–[5]. These antenna configurations provide more than 110% (3.1–10.6 GHz) impedance bandwidth with nearly omnidirectional (OD) radiation patterns from 3 to 6 GHz. Beyond 6 GHz, these printed antennas lose their OD behavior and become more directional.

In real-world scenarios, when these antennas are mounted too close to metal surfaces inside entertainment systems or within handheld devices, they lose their OD nature, and their impedance bandwidths decrease. Also, for short-distance line-of-sight (LOS) applications that only require a limited angular range, an OD pattern is not optimal since most of the power radiates in unwanted directions. In order to provide a good signal-to-noise ratio, antennas with unidirectional or semi-OD (wide-beam) radiation patterns [5] have been proposed. An appropriately designed UWB reflector could provide these advantages along with shielding from nearby metallic objects that can reduce the antenna bandwidth.

Designing such a reflector with a bandwidth of 110% is a challenging task. Classical FSS concepts enhanced by recent developments in periodic structures have led to the creation of perfect magnetic conductors (PMCs) with in-phase reflection, which enable efficient radiation from antennas placed close to the PMC reflector [6]. Planar periodic structures such as FSSs and partial reflecting surfaces (PRSs) are good candidates for integration with printed antennas [7] due to their low planar profile. In [8], a reconfigurable printed dipole array has been examined in the presence of a multilayer FSS. The FSS is positioned in the ground plane of a reflector array aiming to achieve broadband operation by controlling the phase of the reflected wave. In a recent article, an FSS has been used as a backing reflector for extending the frequency range of usability [9]. FSSs have been sandwiched between the antenna and the ground plane, providing an additional reflecting plane for the most critical higher frequency band. In most of these designs, the operation of the FSS has been limited to a narrow frequency band [10], although dual- and wideband operation has been considered in a recent publication [12], exploiting the potential offered by the association of two different elements over a single unit cell, namely a square loop and a crossed dipole. The demonstrated structures show a bandwidth of 52%.

In order to further extend the bandwidth to around 110% to cover the entire FCC-approved UWB band, this letter describes the design of a stacked two-layer FSS that can be used as a reflector for a UWB antenna placed above the FSS. The antenna composite has a theoretical impedance bandwidth of 132%, and the FSS provides reflection-phase coherence (at the antenna plane) over an ultra-wide bandwidth. The performance of the designed FSS as a reflector has been tested with a typical

This work was supported in part by the Australia Research Council, Macquarie University under the iMQRES Scholarship, and the CSIRO ICT Centre under the Top-up Scholarship. The work of L. Matekovits was supported by a Marie Curie International Outgoing Fellowship within the 7th European Community Framework Programme.

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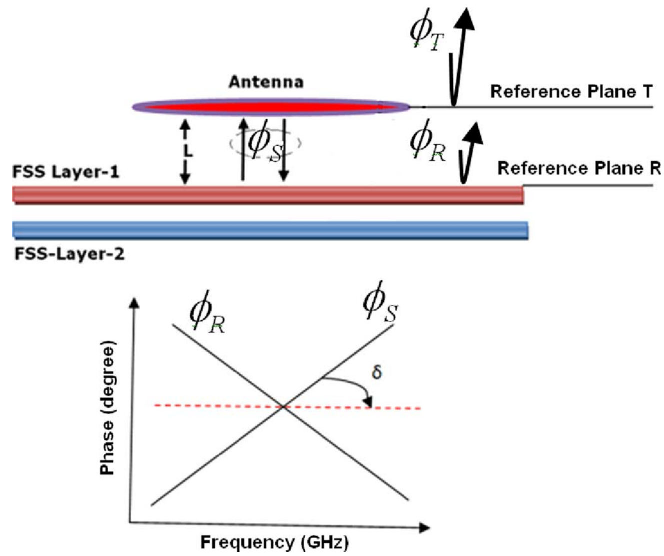

Fig. 1. FSS application for gain enhancement. (*top*) reflection at different frequencies occurs at different layers. (*bottom*) Ideal frequency response of the dual-layer FSS reflection phase ϕ_{R} and phase delay ϕ_{S}.

UWB slot antenna [4]. Significant improvement in the gain over the whole impedance bandwidth has been achieved. Compared to a recently published corrugated reflector arrangement [11], where the antenna shows 21 mm core profile with VSWR < 2.0 from 2.75 to 8.35 GHz and average gain of 6 dBi over the impedance bandwidth, the proposed solution gives a low profile of 18 mm with a much wider bandwidth of 122% and higher gain over the whole bandwidth. All simulations described have been carried out using CST Microwave Studio 2010 [13].

II. Principle and FSS Design

Before proceeding with the FSS design process, its behavior with frequency will be described. In order to gain insight into the multilayer FSS/antenna combination, a schematic describing its operating principle is presented in Fig. 1. Two reference planes have been defined, namely plane R and plane T. To obtain a prescribed phase variation, the two-layer FSS has been optimized over an ultra-wide bandwidth. FSS-Layer-1, which is responsible for providing reflection at higher frequencies, is formed by a set of cross dipoles and square loops. The reflection phase from this layer is ϕ_1. FSS-Layer-2 is designed for lower frequencies and provides a reflection phase of ϕ_2. Both phases refer to reference plane R. The overall phase reflected from the multilayer FSS at the reference plane R is ϕ_{R}. When an antenna is placed at a distance L (mm) above the FSS, the wave radiated toward the FSS is reflected. It will add to the direct, outgoing wave radiated from the antenna in the opposite direction to the FSS reflector. It is expected that the gain of the antenna in the presence of the FSS reflector will be maximum when the two wave components add in phase, giving rise to constructive interference. The evaluation of the phase at the reference plane T is described by the following equations:

$$\phi_{\mathrm{T}} = \phi_{\mathrm{R}} + \phi_{\mathrm{S}} \tag{1}$$

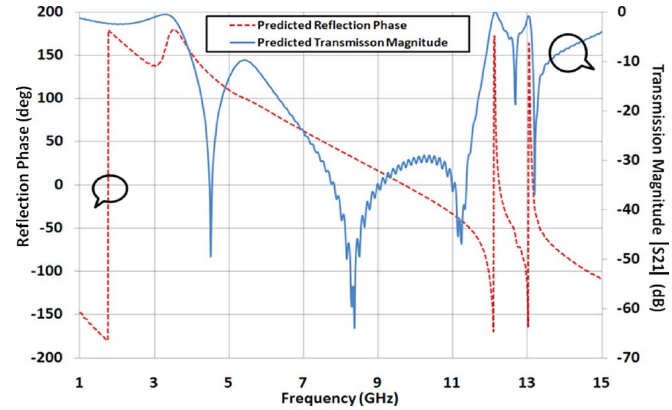

Fig. 2. Predicted reflection phase and reflection magnitude of a dual-layer FSS reflector.

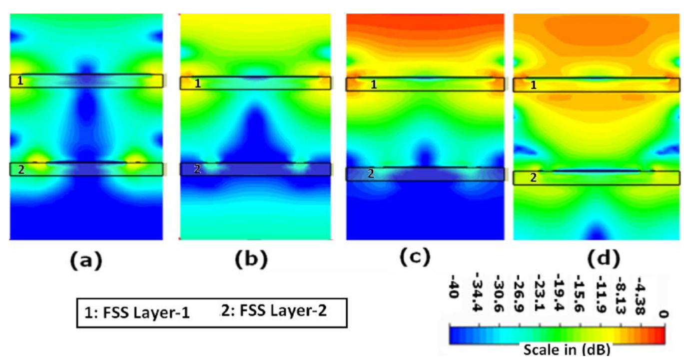

Fig. 3. Electric field distribution orthogonal to the FSS reflector at (a) 3, (b) 6, (c) 8, and (d) 12 GHz.

where $\phi_{\mathrm{R}} = f(\phi_1, \phi_2)$ (at reference plane R) and

$$\phi_{\mathrm{S}} = 2 \times \frac{2\pi f}{c} L.$$

ϕ_{S} is the round-trip free-space propagation phase delay between the antenna and the reference plane R, i.e., the top of the FSS reflector. As stated before, ϕ_1, ϕ_2, and ϕ_{R} are evaluated at reference plane R, while ϕ_{T}, the total reflection phase, is evaluated at reference plane T. For phase coherence, ϕ_{T} should be zero (or an integral multiple of 2π) at all frequencies. Since phase delay ϕ_{S} is frequency-dependent and increases with frequency, the ideal FSS reflection phase ϕ_{R} should decrease with frequency at the same rate. The slope of the ϕ_{S} curve (lower plot in Fig. 1) is controlled by the spacing L between the antenna and reflector. Fig. 2 shows the predicted reflection phase and transmission coefficient of an FSS designed to produce such a coherent reflected wave at the plane of the antenna over an ultra-wide band. The complete design process and FSS parameters are described in Section III.

The dual-layer FSS is capable of providing the required linear decrease in phase over a 120% band while its transmission coefficient is less than -10 dB from 4 to 12 GHz.

The waveguide simulator approach has been used for the analysis of the unit cell. Fig. 3 shows the electric field distribution in the unit cell at 3, 6, 8, and 10 GHz, respectively. It is clearly visible that, at lower frequencies, fields are reflected

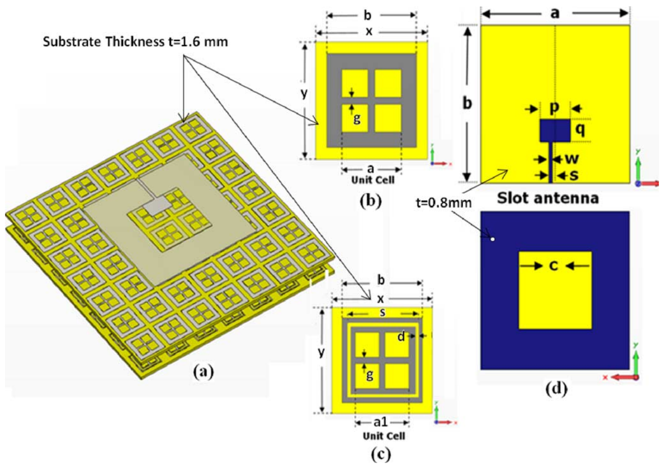

Fig. 4. (a) Complete FSS reflector with a slot antenna. (b) Schematic of unit cells of the FSS Layer 1. (c) Schematic of unit cells of the FSS Layer 2. (d) UWB slot antenna [4], $x = y = 17$, $b = 12$, $g = 0.9$, $t = 1.6$, $d = 1.0$, $a = 10$, $a1 = 8$, $s = 11$, $L1$ (Spacing between two FSS layers) $= 8.5$ mm (all dimensions are in millimeters).

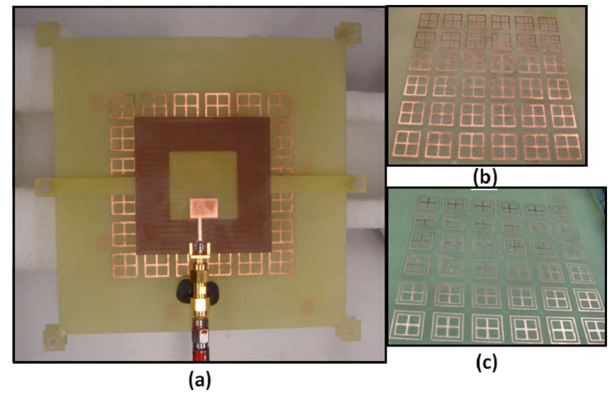

Fig. 5. Photographs of the prototypes: (a) antenna with FSS reflector; (b) FSS Layer 1; (c) FSS Layer 2.

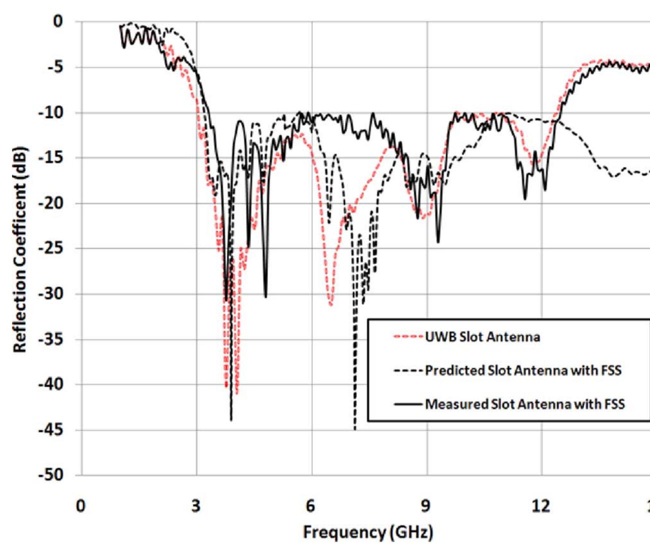

Fig. 6. Input reflection coefficient of the antenna with and without the FSS reflector.

from the lower FSS region. As frequency increases, more reflection occurs from the top layer of the FSS screen. In particular, Fig. 3(c) displays significant reflection above the top layer of the FSS. It corresponds to a transmission coefficient of −50 dB at 8 GHz (see Fig. 2).

III. Antenna With Dual-Layer FSS

A complete schematic of the antenna with reflector is shown in Fig. 4(a). The design process to obtain multioctave bandwidth started with the FSS unit cell that demonstrated a 52% bandwidth in [12]. The unit cell with cross dipole and slot shown in Fig. 4(b) has been redesigned and optimized for use as the top layer of the dual-layer FSS. The waveguide simulator technique has been used to give fast and accurate results. We have also studied the effect of design parameter a on the resonant frequency, which primarily controls the upper UWB band from 8 GHz. When changing this parameter, the FSS reflector resonates at different frequencies between 8.9 and 13.6 GHz. The optimum bandwidth is achieved for $a = 8$ mm. When reoptimizing the unit cell design in [12] to achieve a dual-stopband response and to cover the lower UWB band, we have inserted a rectangular ring slot as shown in Fig. 4(c). The thickness d is optimized to get the maximum possible bandwidth for additional frequencies while maintaining as much as possible the performance of the upper band. For $d = 1.0$ mm, we obtained the maximum bandwidth for the lower band while maintaining the upper bandwidth. Once we have optimized the geometries of these two layers, we stacked them together to form a composite reflector suitable for UWB. Since the gap between the two stacked layers plays a critical role, we have optimized it to achieve a UWB stopband from the composite structure.

After optimizing the FSS screen, a UWB slot antenna excited by microstrip-line-fed patch [4] is mounted above the reflector. This concept is not limited to the particular slot antenna described here; designers can use various other UWB antennas available in literature.

The slot antenna and all FSS reflectors have been designed for fabrication using FR4 substrates with relative permittivity of 4.4 and thickness $t = 0.8$ and 1.6 mm, respectively. A prototype of the assembled antenna and both FSS layers are shown in Fig. 5. The spacing between the antenna and FSS reflector, L, is 9.5 mm.

IV. Measured Results

Radiation patterns and gain of the antenna were measured using an NSI-700S-50 spherical near-field measurement system, while an Anritsu Vector Star Network Analyzer MS4647A (70 MHz–70 GHz) was used for S-parameter measurements. Fig. 6 shows the theoretical and measured reflection coefficients of the slot antenna with and without the dual-layer FSS reflector. The measured impedance bandwidth with the FSS reflector is 122%, which compares well with the predicted bandwidth of 132%. Some small variations between the theoretical and measured data are probably due to fabrication imperfections.

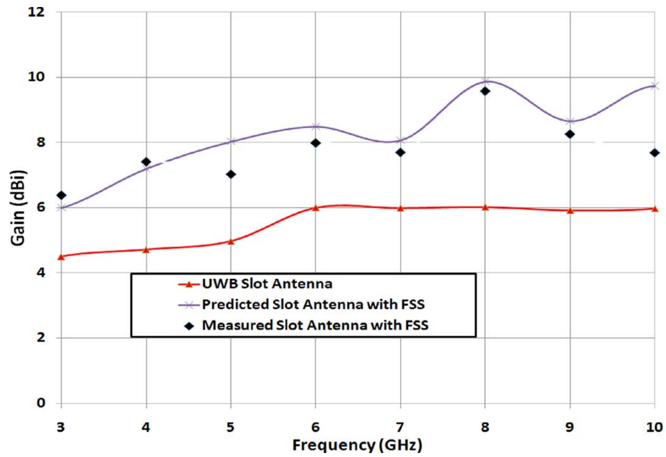

Fig. 7. Predicted and measured gain of the UWB slot antenna with and without the FSS reflector.

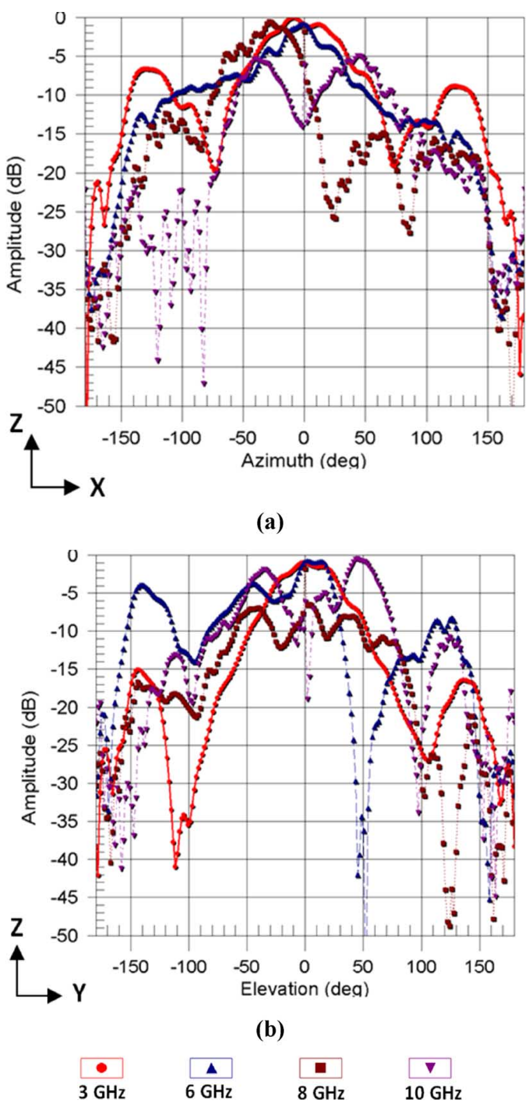

Fig. 8. Measured radiation patterns in (a) xz and (b) yz plane for 3, 5, 8, and 10 GHz.

A maximum gain enhancement of 3.8 dB is achieved at 8 GHz, where the FSS has the lowest transmission coefficient magnitude of -50 dB (see Fig. 2).

The measured gain of the antenna with FSS reflector is shown in Fig. 7, where the theoretical gain of the antenna with and without a reflector is also plotted for comparison. The designed FSS reflects efficiently and enhances the gain of the antenna. A measured gain of around 7.5 dBi up to 7 GHz has been noticed for the proposed solution, while the gain increases up to 9.8 dBi at 8 GHz. Gain variation within the 3–12-GHz band is about 1.8 dBi. The measured radiation patterns at 3, 5, 8, and 10 GHz on the $\phi = 0°$ and $\phi = 90°$ planes are shown in Fig. 8. Due to the offset feed of the slot antenna, the radiation patterns are not symmetrical in these two planes.

V. Conclusion

An ultrawideband reflector combined with a UWB slot antenna has been demonstrated successfully. The low-profile configuration achieves an impedance bandwidth of 122% and an average gain of around 7.5 dBi over the whole UWB frequency band. The dual-layer FSS described should also prove valuable for many other applications requiring a low-profile reflector with wideband performance. When the proposed FSS is used as the separator/shield, the considered UWB antennas can be fitted close to and parallel to the conducting surfaces (such as metal cases, screens) commonly found in modern microwave and wireless devices. It has been verified that its use prevents deterioration of the antenna impedance mismatch and increases antenna gain.

References

[1] H. Schantz, *The Art and Science of Ultrawideband Antennas*. Norwood, MA: Artech House, 2005.

[2] K. P. Ray and Y. Ranga, "Ultra wideband printed elliptical monopole antenna," *IEEE Trans. Antennas Propag.*, vol. 55, no. 4, pp. 1189–1192, Apr. 2007.

[3] K. P. Ray and Y. Ranga, "Ultra-wideband printed modified triangular monopole antenna," *Electron. Lett.*, vol. 42, no. 19, pp. 1081–1082, Sep. 2006.

[4] H.-D. Chen, J.-S. Chen, and J.-N. Li, "Ultra-wideband square-slot antenna," *Microw. Opt. Technol. Lett.*, vol. 48, no. 3, pp. 500–502, Jan. 2006.

[5] A. Sibille, S. Bories, R. D'Errico, and C. Roblin, "UWB antenna performance evaluation from the communication system point of view," in *Dig. 3rd ISWCS*, Sep. 6–8, 2006, pp. 417–422.

[6] N. Engheta and R. W. Ziolkowski, *Electromagnetic Metamaterials: Physics and Engineering Explorations*. Hoboken, NJ: Wiley–IEEE Press, 2006.

[7] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*, 1st ed. New York: Wiley-Interscience, 2000.

[8] Y. E. Erdemli, K. Sertel, R. A. Gilbert, D. E. Wright, and J. L. Volakis, "Frequency selective surfaces to enhance performance of broad-band reconfigurable arrays," *IEEE Trans. Antennas Propag.*, vol. 50, no. 12, pp. 1716–1724, Dec. 2002.

[9] M. Pasian, S. Monni, A. Neto, M. Ettorre, and G. Gerini, "Frequency selective surfaces for extended bandwidth backing reflector functions," *IEEE Trans. Antennas Propag.*, vol. 58, no. 1, pp. 43–50, Jan. 2010.

[10] G. I. Kiani, A. R. Weily, and K. P. Esselle, "A novel absorb/transmit FSS for secure indoor wireless networks with reduced multipath fading," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 6, pp. 378–380, Jun. 2006.

[11] Q. Wu, J. Ronghong, G. Junping, and S. Donglin, "On the performance of printed dipole antenna with novel composite corrugated-reflectors for low-profile ultrawideband applications," *IEEE Trans. Antennas Propag.*, vol. 58, no. 12, pp. 3839–3846, Dec. 2010.

[12] R. M. S. Cruz, A. G. D'Assunao, and P. H. da F Silva, "A new FSS design proposal for UWB applications," in *Dig. iWAT*, Mar. 1–3, 2010, pp. 1–4.

[13] CST Microwave Studio Computer Simulation Technology, Framingham, MA, 2010 [Online]. Available: www.cst.com