Size Reduced Array Antenna with Enhanced Directivity

Sheikh S. I. Mitu and Farooq Sultan

Department of Electrical Engineering
King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
sheikhsi@kfupm.edu.sa, farooqstn@hotmail.com

Abstract ─ Small array antennas with directive coverage are an attractive solution for size limitation in wireless devices. In this paper, the design of a directive 10 GHz antenna with reduced size microstrip array and frequency selective superstrate (FSS) is presented. Inductive loading and reduced patch separation is used to incorporate 7-elements within a 100x30 mm^2 array aperture. The superstrate (FSS) layer is optimized to properly excite the Fabry-Perot cavity and further increase the antenna directivity. Using HFSS software, the reflection response and the radiation pattern of the antenna array is optimized. The simulated responses agreed well with the measured results.

Index Terms ─ Antenna array, enhanced directivity, frequency selective surface, inductive loading, shorting posts.

I. INTRODUCTION

Recent communication devices require miniature microstrip array antennas with high directivity and reconfigurable coverage. Over the past decade, many techniques have been adopted to reduce the size of a microstrip antenna without sacrificing its directivity. One method to reduce antenna size is to use high dielectric constant (ε_r) substrate, but this comes at the cost of increased surface wave losses [1]. Another popular technique is to introduce electrical short between the patch and the ground plane to reduce the antenna size [2]. Shorting posts are modeled as a short piece of transmission line, which introduces a series inductance and a shunt capacitance due to self-inductance and close proximity of the shorting posts, respectively [3]. By optimizing the diameter, number and separation of the shorting posts, the desired resonant response of the antenna can be achieved [4].

The directivity and beam forming characteristics of a uniform microstrip array antenna are controlled through the magnitude and phase of the patch excitation signals [5]. Controlling the input excitation, however, requires the design of complicated array feeder networks to ensure correct magnitude and phase values are fed to the radiating elements [6]. An alternative is to use a Fabry-Perot cavity (FPC) resonator, formed between the array of microwave radiators and a partially reflecting frequency selective superstrate (FSS) [7]. A side view of an FPC excited by a 7-element array is shown in Fig. 1. Multiple reflections inside the cavity result in constructive addition of the signal resulting in stronger radiated signal. To achieve maximum directivity, design parameters like height, size, position and composition of the cavity and the superstrate need to be optimized. This allows the cavity resonator to build up required field distribution without introducing significant resonator losses [8]. Through proper excitation, the side-lobe level (SLL) of the FPC antenna can also be controlled.

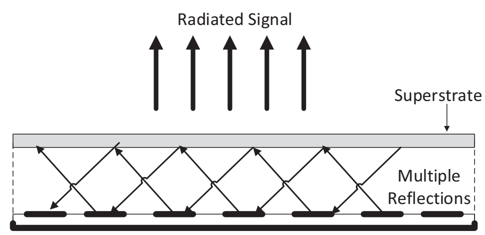

Fig. 1. Side view schematic of an FPC excited by a 7-patch linear antenna array.

In this paper, the positions and dimension of the shorting posts are carefully selected to reduce the width of the 10 GHz shorted patch array antenna by 50%. To further increase the antenna directivity, this 7-element linear array is used to optimally excite the FPC formed between the array ground and an optimally designed FSS.

II. SHORTED ANTENNA ARRAY DESIGN

Initially a $(3.3\times1)\lambda_0$ or a 100x30 mm^2 antenna aperture was selected for the 10 GHz antenna array. For a patch separation of $0.5\lambda_0$, a maximum of 3-radiating patches were accommodated within the array aperture, as shown in Fig. 2 (a). The aim was to improve the directivity by increasing radiating patches within the same array aperture. This required shortening the patch width (W_p) with minimum effects on array efficiency, matching and radiation pattern. Based on the impedance distribution of a radiating patch, shorting posts were introduced to neutralize the changes in the input impedance due to shortening the patch width. The number, location and radius of the shorting

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posts were optimized to accommodate 7-radiating shorted patches; instead of 3-radiating normal patches within the array aperture of 100 mm.

The 10 GHz array antenna with 7 shorted-patches is shown in Fig. 2 (b). Note that both antenna arrays of Fig. 2 are based on a 100 mm ($W_T = 3.3\lambda_0$) wide Duroid substrate with $\varepsilon_r = 2.2$ and thickness, h = 1.6 mm. The antenna dimensions of the 3-patch 10 GHz array of Fig. 2 (a) were $L_p = 0.32\lambda_0$ (9.5 mm), $W_p = 0.45\lambda_0$ (13.6 mm) and $d_2 = 0.5\lambda_0$. The design parameters for 7-patch array shown in Fig. 2 (b) were $L_p = 0.32\lambda_0$ (9.5 mm), $W_p = 0.13\lambda_0$ (4 mm) and $d_2 = 0.37\lambda_0$. Three shorting posts, each with a radius of 0.25 mm and inter-post separation of 0.5 mm were placed inside each of the 7 rectangular patches. This reduced the width of each 10 GHz patch by more than 50% and allowed the replacement of the 3x1 patch array with 7x1 shorted-patch array on the same array aperture of $3.3\lambda_0$ (100 mm).

The simulated reflection responses of the 3-element and the 7-element array are superimposed in Fig. 3. Note that the shorted patches with reduced inter-element distance (d) have little effect on the impedance bandwidth of the antenna. The radiation patterns of these two antennas are plotted in Fig. 4, without including the feeder losses. As expected, the 7-element array exhibited a 25% increase in the antenna directivity.

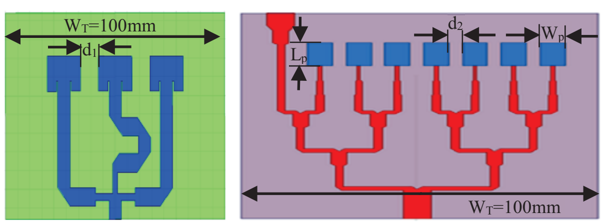

Fig. 2. 10 GHz array antenna with: (a) 3-element array of standard patches with inter-element spacing, $d_1 = 0.5\lambda_0$ and, (b) 7-element array of shorted patches with inter-element spacing, $d_2 = 0.37\lambda_0$.

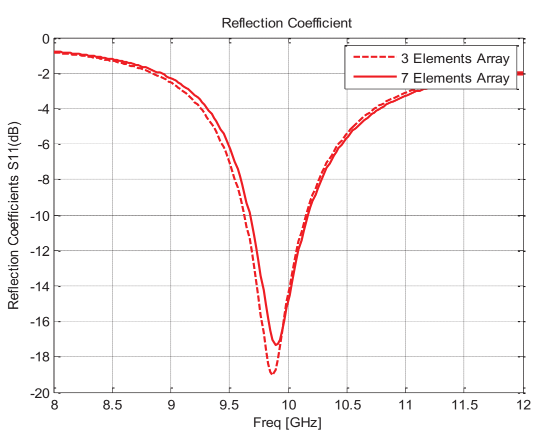

Fig. 3. Simulated reflection response (S_{11}) of the 3-element and the 7-element shorted patch antenna array.

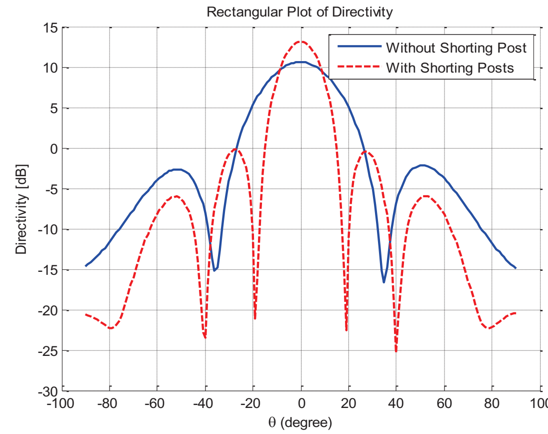

Fig. 4. Simulated E-plane radiation patterns of the 3-element and the 7-element shorted-patch array.

III. SHORTED ARRAY WITH FREQUENCY SELECTIVE SUPERSTRATE

To further increase the antenna directivity, the 7-element shorted patch array is used to excite an FPC resonator, formed between the array ground plane and the partially reflecting superstrate. Figure 5 shows the HFSS simulated model of the FPC antenna with FSS with the inset showing the dimensions of the dipole unit-cell. The shape and design of the FSS unit-cell plays a vital role in determining the response of the superstrate layer. Amongst the numerous unit-cell configurations used in literature [9], the simple design and ease in fabrication associated with the dipole unit-cell has made it the choice for the proposed FPC antenna array. The dimensions of the dipole unit-cell have been extracted using the empirical relations presented by Lee et al. in [10], and optimization has been achieved by using plane wave simulations in HFSS [11].

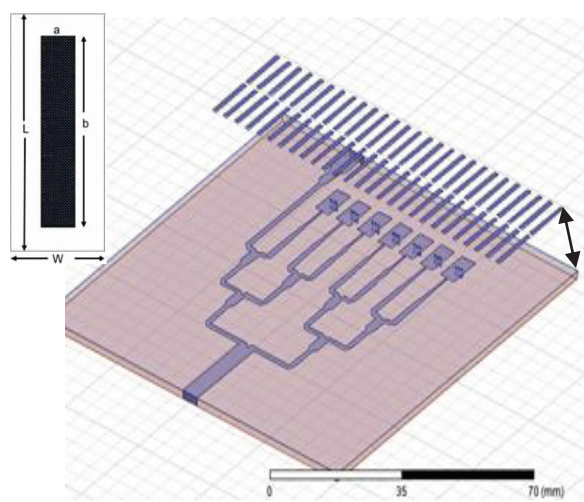

Fig. 5. HFSS simulation model of the 7-patch shorted antenna array with FSS layer forming the FPC.

To cover the entire aperture (100x30 mm^2) of the antenna array, the FSS required two layers of dipole unit-cells with 27 unit cells per layer as shown in Fig. 5. The simulated results demonstrate maximum radiation at 10 GHz for optimized cavity height (h) of 0.5λ_0 (16 mm) and dipole unit-cell parameters of L = 0.49λ_0 (14.76 mm), W = 0.12λ_0 (3.69 mm), a = 0.04λ_0 (1.23 mm) and b = 0.45λ_0 (13.58 mm). This FSS layer can be implemented by using the packaging of the antenna. The formulation of the FPC using the FSS layer results in a 3.21 dB increase in the simulated directivity of the shorted 7-patch antenna array. Figure 6 shows the simulated E-plane radiation patterns with and without the FSS layer. As a result of an increased number of radiating elements, the shorted 7-patch antenna array has a simulated radiation efficiency of 73.15% which is 3.23% less than the 3-patch normal array. Placement of the FSS results in a further decrease in the simulated efficiency of the 7-element shorted antenna from 73.15% to 69.88%. In addition to the increase in peak directivity, an increase in the SLL is also observed, which can be countered by embedding the FSS on a stepped dielectric superstrate; a dielectric superstrate with varying ε_r. The reason for reduced SLL is the uneven partial reflections from the stepped dielectric superstrate, with central low-ε_r material sandwiched between the high-ε_r materials.

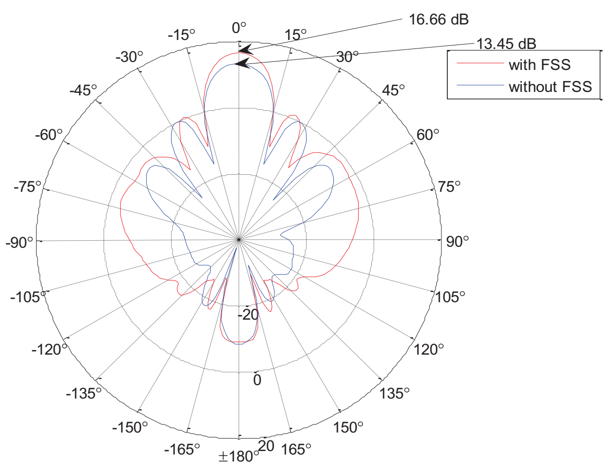

Fig. 6. Simulated E-plane directivity pattern comparison for the shorted 7-patch antenna array with and without the FSS.

IV. MEASUREMENT RESULTS

The 7-patch shorted antenna array along with the FSS has been fabricated according to the design parameters mentioned in Sections II and III. A snapshot of the fabricated FPC antenna array is shown in Fig. 7. Upon measuring the reflection characteristics of the fabricated antenna array, it is evident from Fig. 8 that addition of the FPC results in a slight decrease (100 MHz) in the resonant frequency (9.8 GHz) as compared to the no FSS case (9.9 GHz). Additionally the impedance bandwidth of the FPC antenna also increases to 530 MHz as compared to 253 MHz for the without FSS case. A view of the measured E-plane directivity of the designed antenna, shown in Fig. 9, reveals that the addition of the FSS, and hence the formation of the FPC, results in a further increase of 3.41 dB in the measured directivity of the antenna. Note that, although for the directivity measurements the antenna array was used as a receiver, owing to reciprocity, the same performance is expected if used as a transmitter.

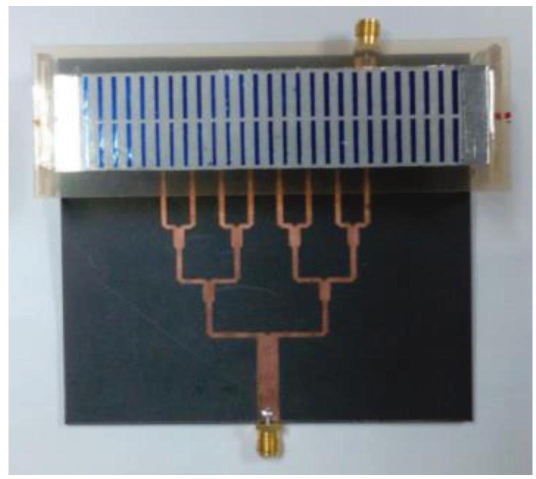

Fig. 7. Fabricated shorted 7-patch FPC antenna array with dipole unit-cell based FSS superstrate.

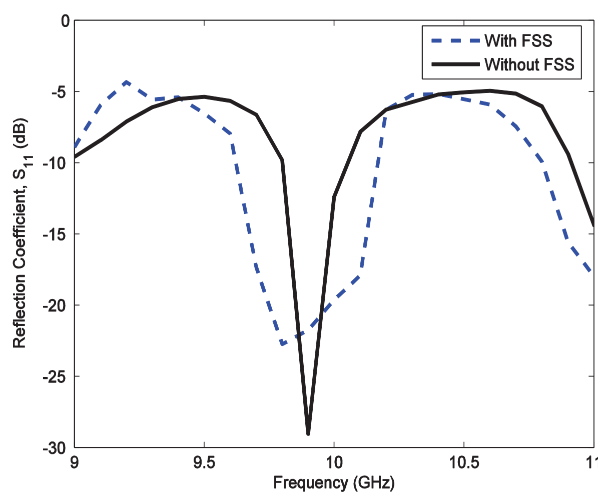

Fig. 8. Reflection characteristics (S_{11}) for the shorted 7-patch antenna array with and without the FSS superstrate.

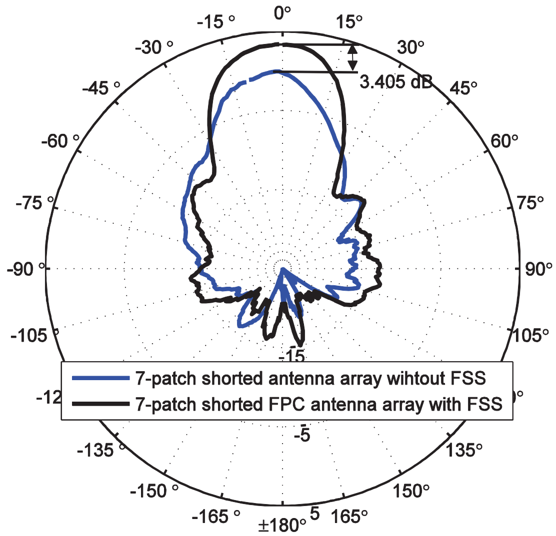

Fig. 9. Measured E-plane directivity patterns for the shorted 7-patch antenna array with and without the FSS superstrate.

V. CONCLUSION

The design of a 100x30 mm^2 linear array antenna with 7-shorted patches and a frequency selective superstrate is presented. The antenna demonstrated an increased directivity of 6.2 dB due to increased number of radiating elements and optimized resonance by FPC using a dipole unit-cell based FSS. Inductive loading of the radiating patches enables placement of 7 radiating elements instead of 3 within the fixed antenna aperture of 3.3λ_0 (100 mm). The thickness of the cavity is optimized to keep the antenna dimensions small. Since all the design parameters are a function of the operational wavelength (λ_0), the presented antenna design can be scaled to any frequency of operation. The measured results agree well with the simulated (HFSS) responses of the antenna presented design.

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Sheikh Sharif Iqbal Mitu is an Associate Professor in EE Department of KFUPM, Dhahran, KSA. He has completed his M.Sc. and Ph.D. degrees from the EEE Department of University of Manchester, UK. He has authored 55+ referred journal/ conference papers, 30+ technical reports and worked/working with 25+ projects funded by university, government (SABIC, KACST) and industry (Schlumberger).

He is a Fellow of IET, Senior Member of IEEE and Honorary Treasurer of IET Saudi section. His achievements includes several awards related to teaching, research and supporting student activities.

Farooq Sultan completed his M.Sc. and Ph.D. degrees from KFUPM, Dhahran, Saudi Arabia. His research interests comprise mainly of antenna array designs; however, he also has experience in wireless sensor network designs for practical applications. He has extensive research experience with antenna array designs and has authored/co-authored a number of journal as well as conference publications along with a few US patents.

Currently, he chairs the Student Branch of the IEEE KFUPM section and is an IEEE Student Member as well.