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Dual-Slot Feeding Technique for Broadband Fabry-Perot Cavity Antennas

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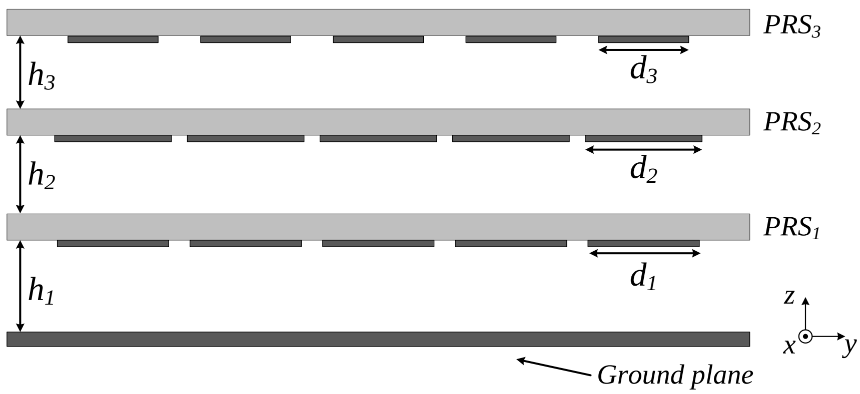
***Abstract*— A dual-slot feeding technique is proposed for broadband multi-layer periodic Fabry-Perot cavity antennas achieving enhanced directivity as well as broadband radiation and matching performance. In order to demonstrate the feeding technique, two FPC antennas are presented formed by two- and three-layer periodic Partially Reflective Surfaces (PRSs) respectively placed in front of a ground plane. Two optimized microstrip-fed rectangular slots of different length etched on the ground plane are used to feed the multi-layer cavity antennas and significantly enhance the antenna bandwidth as well as the directivity performance. Measurements of a fabricated three-layer PRS antenna prototype are presented exhibiting 19 dBi gain with 16% fractional bandwidth and validating the simulation results.**

Index Terms— Fabry-Perot cavity (FPC); Leaky-wave antennas; Partially reflective surfaces.

1. INTRODUCTION

Fabry-Perot cavity antennas have been investigated extensively in the last few years [1-3]. They are formed by partially reflective surfaces (PRSs), either periodic metallo-dielectric arrays [1-3] or uniform dielectric layers [4, 5], placed in front of a low-directivity source (e.g. dipole) over a metallic ground plane, creating a resonant Fabry – Perot cavity (FPC). The directivity and gain of the primary source increase significantly due to the cavity resonance and the multiple reflections between the ground plane and the PRS. The antenna performance can be related to the reflection characteristics of the PRS array by employing a plane wave model that can be used for an initial antenna design. However, this type of antennas has narrow operational bandwidth. Recently an FPC antenna based on a double layer PRS [6] has been proposed with enhanced bandwidth compared to a single layer PRS design. Furthermore in [7], bandwidth enhancement was achieved by using two dielectric superstrates. In [8], the possibility of using additional PRS layers in FPC antennas was presented, showing further enhancement of the radiation bandwidth. However, as the radiation bandwidth of FPC antennas increases, the input matching becomes more challenging. Various broadband matching feeding techniques have been proposed, such as coaxial fed patches [9, 10] and monopoles [6]. Nevertheless, these techniques are not scalable to mm-wave frequencies as the use of coaxial cables is not applicable. In addition, in the reported designs, the primary feeding is located within the first resonant cavity and in some cases in the middle of the cavity which affects the antenna's performance.

In this paper, we present a new dual-slot dual-resonant feeding technique for two- and three-layer-PRS broadband FPC antennas, achieving a broadband matching performance as well as increased directivity and gain. It must be emphasized that the proposed optimized feeding slots are of different length and they exhibit two significant enhancements in the antenna performance, namely broadband input matching and increase of the directivity. Moreover, as they are excited by a microstrip line, they are based on printed layer fabrication process and thus they are directly scalable to higher frequencies. Full wave periodic simulations are initially carried out using CST Microwave Studio™ in order to optimize the antenna design. Measurement results of a fabricated prototype are also presented.



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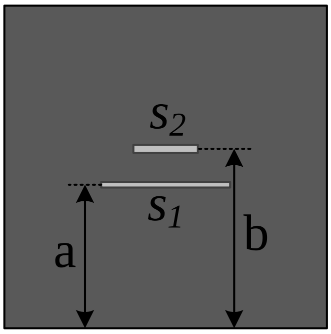

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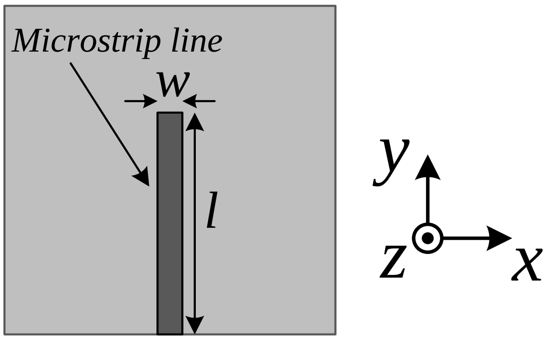


(c)

Fig. 1. Schematic diagram of the proposed antenna
(a) Cross section of the structure
(b) Front view of ground plane with slots of length s_{xi} and width s_{yi}
(c) Back view of the ground plane (microstrip line).

2. DESIGN OF DUAL-SLOT FEEDING TECHNIQUE

The design of the proposed dual-slot feeding structure that is used in later sections in broadband FPC antennas is presented in this section. As already mentioned in the Introduction, we have chosen a microstrip fed slot antenna design which is easily scalable to higher frequencies. A microstrip line is printed on a 1.6mm thick dielectric substrate with an electric permittivity ε_r=2.2 and a tangent loss tanδ=0.009 (Fig. 1c). The ground plane is printed on the other side of the substrate and the feeding slot/s are etched off it. This structure is based on chemical etching printed circuit board fabrication process. In order to evaluate the operation frequency and bandwidth of the proposed feeding structure, the latter has been simulated.

Initially an approximately half wavelength rectangular slot was etched on the ground plane located in the centre of the plane, above the microstrip line. The dimensions of the slot were selected such that a resonance would occur within the frequency range of interest and are presented in Table 1. In the same table the dimensions of the microstrip line are also included. The $|S_{11}|$ response for the single slot feeding is shown in Fig. 2. It can be observed that the $|S_{11}|$ is below -10dB from 13.8GHz to 15.2GHz corresponding to a fractional bandwidth of 10%, with a minimum occurring at 14.5GHz which is the central frequency of the multi-layer antenna.

Subsequently, a second slot of different dimensions has been added as shown in Fig. 1(b), introducing an extra coupling which in turn is expected to cause a more broadband response. The dimensions (length s_{xi} and width s_{yi}) and the distance between the slots are shown again in Table 1. The $|S_{11}|$ response for the dual slot feeding is also shown in Fig. 2. It is evident that indeed a more broadband (tripled) matching is achieved with the $|S_{11}|$ being below -10dB from 12.8GHz to 17GHz corresponding to about 30% fractional bandwidth. Two minima occur in this case, at 13GHz and 15.5GHz related to the dual resonance of the structure. It must be noted that the optimisation that led to the design presented here was also carried out with in the presence of the entire FPC antennas in order to ensure a successful operation of the final antenna prototypes.

TABLE 1

PARAMETER VALUES (MM) FOR FEEDING STRUCTURE

Parameter (single slot)	a		w	*l*	s_x		s_y	
Value	40		4.8	50.5	14.8		1	
Parameter (dual slot)	a	b	w	*l*	s_{x1}	s_{x2}	s_{y1}	s_{y2}
Value	37.6	42.5	4.8	50.5	18.5	8.2	1	1.5

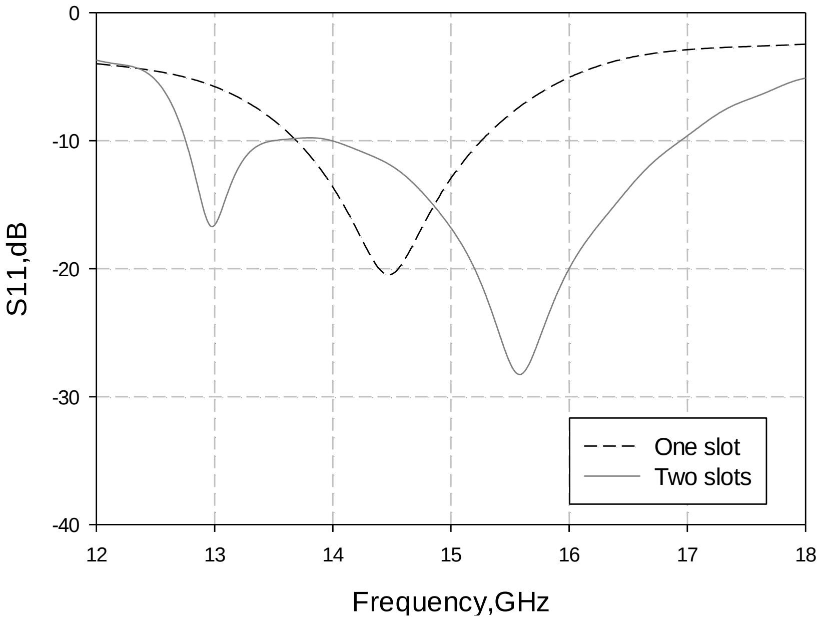


Fig. 2. Comparison of the $|S_{11}|$ between one and two microstrip fed slots as primary source.

In order to further evaluate the advantages of the dual-slot feeding structure, an inspection of the near-field distribution is carried out. In Fig. 3, a cross section of the electric field for the single slot and the dual-slot is presented at 14GHz. It is evident that in the case of the two coupled slots a more uniform near field distribution is obtained than in the case of the single slot. This is effect is particularly advantageous in the case of the FPC antennas studied in the later sections, as it contributes to a significant enhancement of the overall antenna directivity.

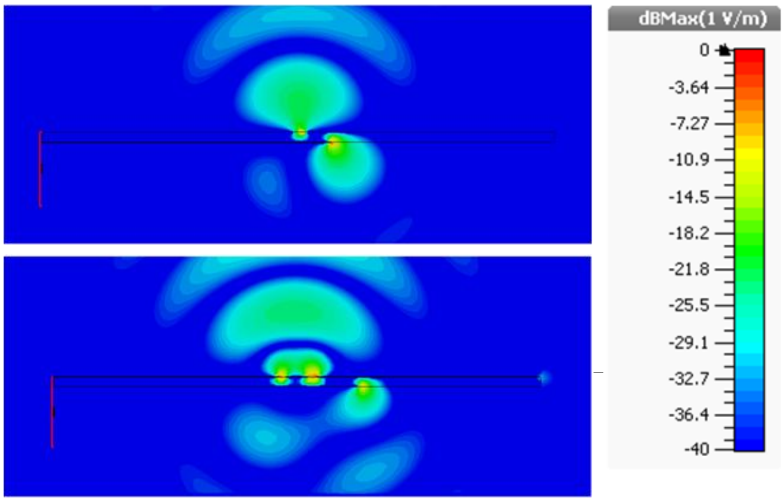


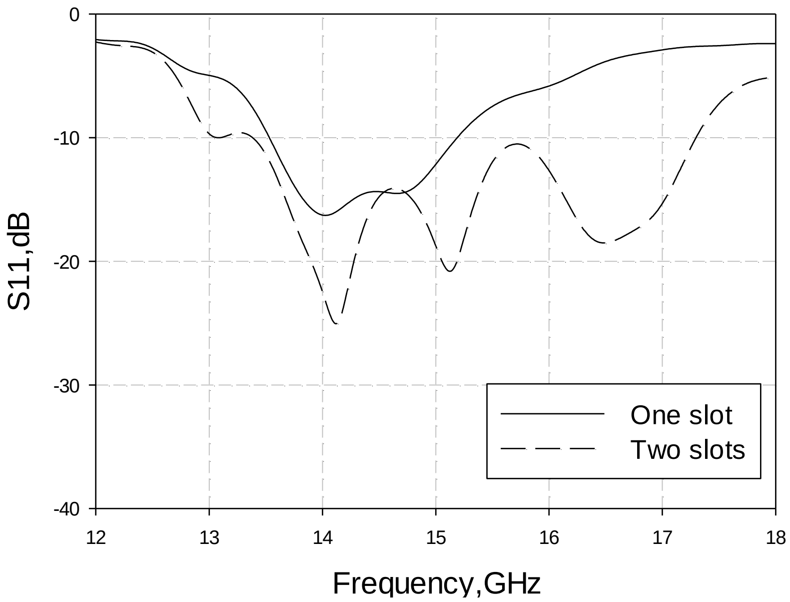
Fig. 3. Cross section of the electric field distribution (YZ plane) for the ground plane with one (top) and two (bottom) slots.

3. ANTENNA DESIGN

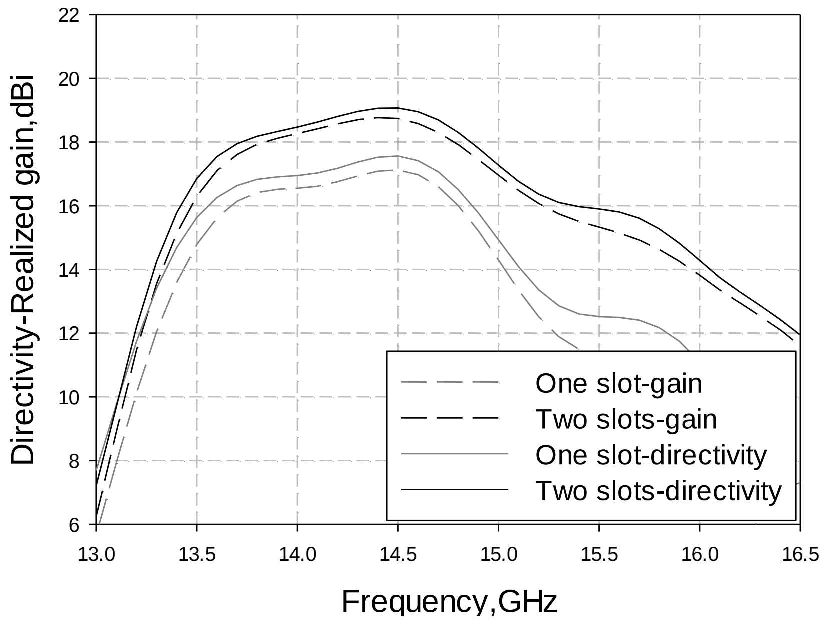
A. Double Layer Antenna

Initially, a double layer PRS antenna is designed. Two periodic PRS layers are used, printed on a 1.6mm thick dielectric substrate (Taconic TLY–5) with relative permittivity of 2.2. The layers are placed in front of a ground plane forming two air cavities of approximately half wavelength each. The complete structure is similar to the one presented in Fig. 1(a) with two PRS layers instead of three. Metallic square elements have been chosen for the proposed design. The periodicity is 11mm. The dimensions of the elements of the unit cells are d_1=10mm, d_2=6mm and the distances between the layers are h_1=11.3mm, h_2=11mm. Periodic boundary conditions have been employed in CST in order to optimize the dimensions following the design procedure reported in [6]. The overall lateral dimensions of the antenna are $80*80\,\mathrm{mm}^2$, which correspond to about 4λ at 14.5GHz. A total of $5*5$ array elements are printed on each dielectric layer. The antenna is fed by two rectangular sub-wavelength slots on a ground plane. A 50Ω microstrip line is used to excite the slots, printed on a same thickness substrate. The two slots are etched on the ground plane which lies on the other side of the substrate (Fig. 1b, c) as explained in Section 2.

The complete antenna structure was simulated in CST Microwave Studio. Both the single slot and the dual-slot feeding structures have been incorporated with the multi-layer antenna for comparison. The $|S_{11}|$ response for the single slot feeding is shown in Fig. 4(a). It can be seen that the $|S_{11}|$ is below -10dB from 13.6GHz to 15.2GHz. The $|S_{11}|$ response for the optimised dual-slot feeding is also presented in Fig. 4(a). With the proposed dual-slot technique, the $|S_{11}|$ remains below -10dB within a much broader frequency range compared to the single-slot feeding and covers the entire antenna operating bandwidth. Moreover from Fig. 4(b), it can be observed that the gain and directivity of the antenna are also improved with the dual-slot feeding, achieving a maximum gain of around 18.7dBi at 14.5GHz, compared to 17.1dBi for the single slot case. Also, the difference between the directivity and gain is less in the case of the dual-slot feeding due to the improved matching performance. The -3dB gain bandwidth of the antenna is around 12.2%.



(a)



(b)

Fig. 4. Comparison between one and two microstrip fed slots as primary source of the double layer PRS antenna in terms of

(a) $|S_{11}|$

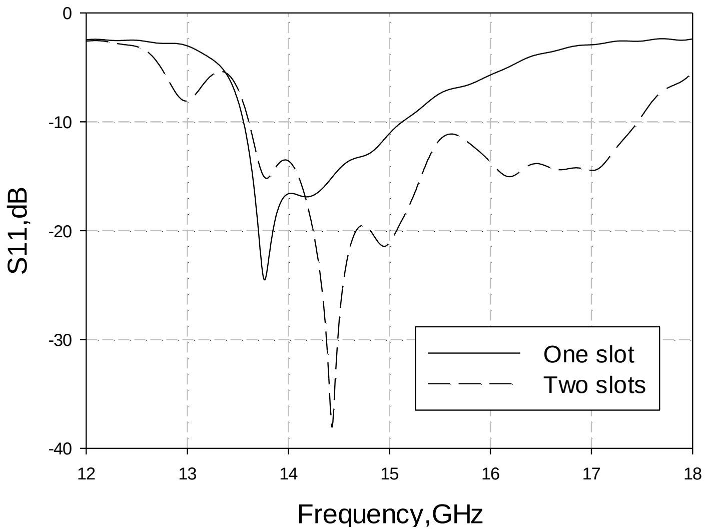
(b) Realized Gain and Directivity.

B. Three Layer Antenna

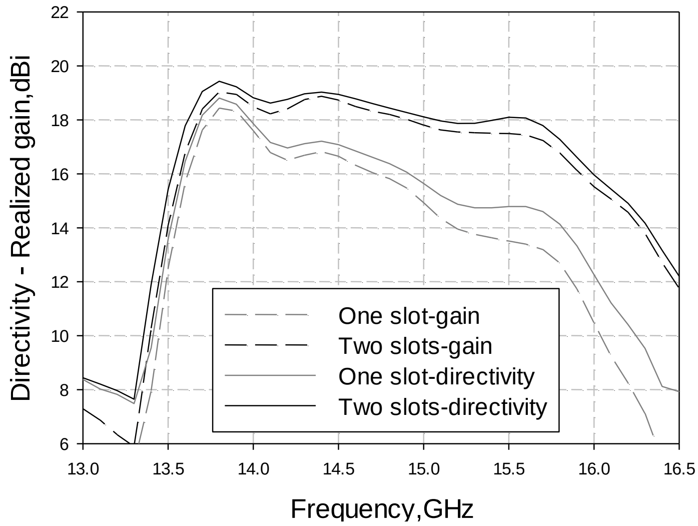
Three optimised PRS layers are employed next, to achieve a more broadband antenna performance. The three periodic PRS layers are printed on similar dielectric substrates as in the double layer case. The layers are placed again in front of a ground plane forming three air cavities of approximately half wavelength each (Fig. 1a). The dimensions of the unit cells as well as the distances between the layers have been optimized through simulations in CST Microwave Studio and are shown in Table 2.

The $|S_{11}|$ response for the case of a single slot feeding is shown in Fig. 5(a). It is evident that the achieved -10dB matching does not cover all the desired frequency range, causing a deterioration of the realized antenna gain (Fig. 5b). The introduction of the second slot yields a more broadband input matching that covers all the operational frequency range. From Fig. 5(a) it can be seen that for this case the $|S_{11}|$ is below -10dB from 13.6GHz to 17.4GHz. Moreover from Fig. 3(b), it can be observed that there are very small discrepancies between the directivity and the gain in the case of the two slots, as expected. In comparison, for the single slot feeding the difference between the directivity and gain is increased, especially at higher frequencies with a maximum of about 2dB, due to the poor matching at frequencies higher than 15.1GHz. The complete dual-slot-fed antenna structure achieves a maximum gain of around 19dBi (Fig. 5b) with a -3 dB gain bandwidth of 16%. It is interesting to note that, as in the case of the double-layer PRS antenna, the dual-slot feeding not only improves the input matching but it also increases significantly the antenna directivity.

In order to further investigate the directivity enhancement due to the dual-slot feeding mechanism, the electric near-field distribution for the three layer antenna with one and two feeding slots is shown in Fig. 6, providing a better insight of the dual-slot operation. For brevity, we present the YZ cross section of the field distribution only at 14GHz and 15GHz. It can be observed that the field distribution is significantly improved (i.e. becomes more uniform) with the proposed feeding technique compared to the single slot at both frequencies as expected from the investigation of the feeding structures. This explains the significant directivity enhancement of more than 3dBs at frequencies over 15GHz (Fig. 5b).



(a)



(b)

Fig. 5. Comparison between one and two microstrip fed slots as primary source of the three layer PRS antenna in terms of:

(a) $|S_{11}|$

(b) Realized Gain and Directivity

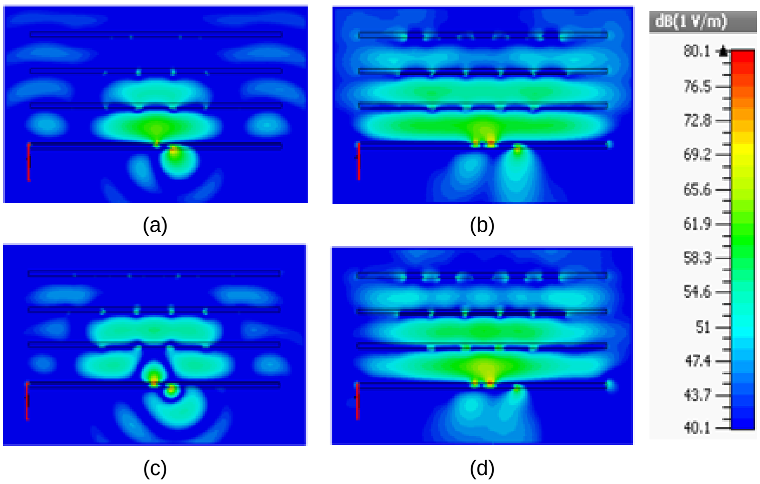


Fig. 6. Cross section of the electric field distribution (YZ plane) for the three layer antenna
(a) One slot at 14GHz
(b) Two slots at 14GHz
(c) One slot at 15GHz
(d) Two slots at 15GHz.

TABLE 2
PARAMETER VALUES (MM) FROM FIG. 1

Parameter	h_1	h_2	h_3	d_1	d_2	d_3
Value	11.3	9.5	10	9.2	10	6

4. MEASUREMENTS

A prototype of the proposed antenna has been fabricated and measured in a full anechoic chamber (Fig. 7). Plastic screws and spacers were used for the mounting of the antenna. The simulated and measured $|S_{11}|$ of the antenna is presented in Fig. 8(a). An $|S_{11}|$ below -10dB is achieved within the -3dB gain bandwidth of the antenna which is around 15%. The measured gain with a maximum value of 18.7dB is shown in Fig. 8(b) and agrees well with the simulation results. The small discrepancy between simulations and measurements is attributed to fabrication tolerances. Moreover the well known gain transfer method was used which implies a ±0.5dB error introduced by the gain of the reference broadband horn antenna. The H- and E-plane patterns where measured in three different frequencies within the operating band. Simulated and measured results are presented in Fig. 9. In all frequencies good agreement has been achieved.

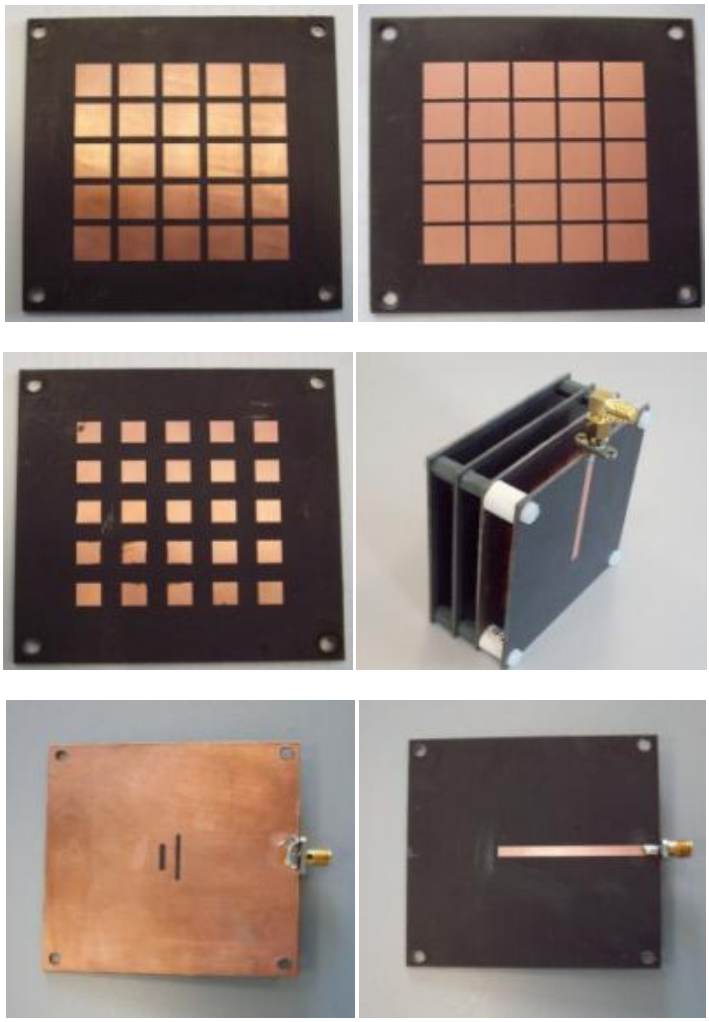
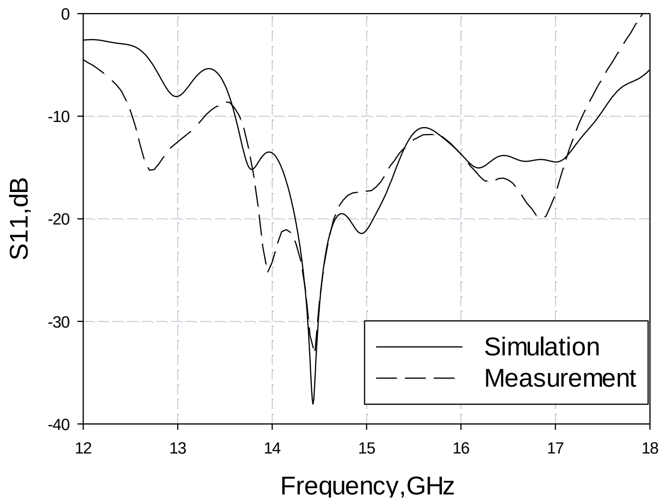
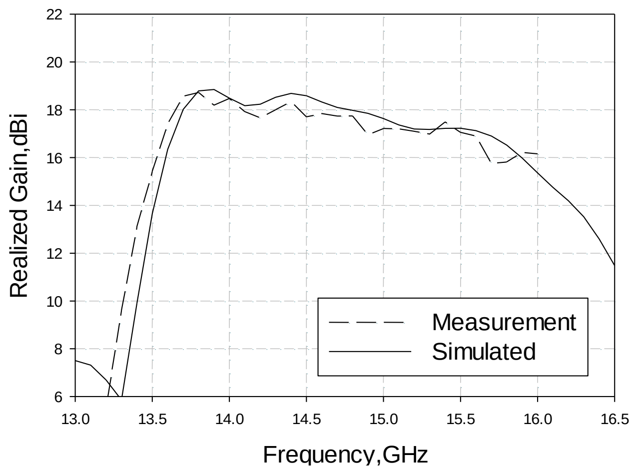


Fig. 7. Photograph of the fabricated prototype (three PRS layers, assembled antenna and both sides of ground plane).



(a)

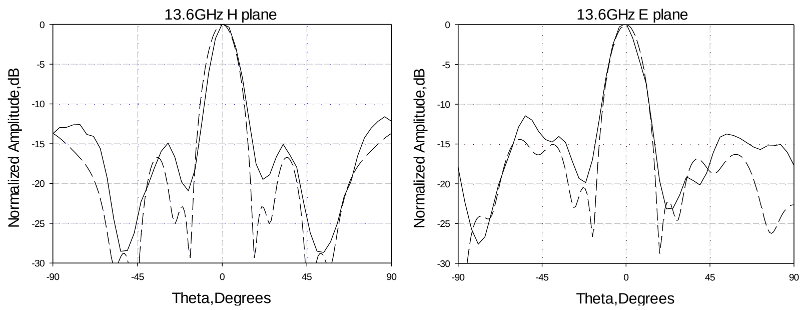


(b)

Fig. 8. Comparison between measurement and simulation for the proposed antenna for:
(a) $|S_{11}|$
(b) Realized Gain

5. CONCLUSIONS

A new dual-slot dual-resonant feeding technique for two- and three-layer-PRS FPC antennas has been presented achieving a broadband matching performance and an increased directivity and gain. A maximum antenna gain of around 18.7dBi and 19dBi has been achieved for the two- and three-layer antennas respectively with a -3dB gain bandwidth of 12.2% for the two-layer and 16% for the three-layer case. Measured results for a fabricated prototype of the three-layer antenna have been presented and are in good agreement with simulation predictions.



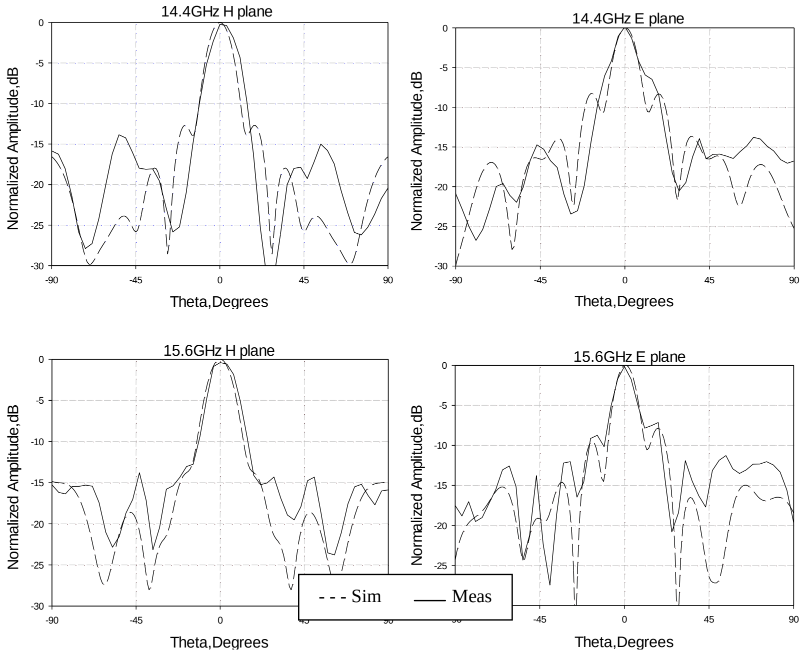


Fig. 9. Simulated and measured radiation patterns.

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