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Published in:
Microwave, Radar and Wireless Communications (MIKON), 2016 21st International Conference on

DOI (link to publication from Publisher):
10.1109/MIKON.2016.7491945

Publication date:
2016

Document Version
Early version, also known as pre-print

Low-Profile Fabry-Pérot Cavity Antenna with Metamaterial SRR Cells for Fifth Generation Systems

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***Abstract*—This manuscript deals with the design and performance validation of a compact Fabry-Pérot cavity (FPC) antenna for the fifth generation (5G) system applications. The configuration of the proposed design includes a primary coaxial-fed radiator backed with a full ground plane, an air cavity, and a partially reflecting surface (PRS) with a 4×4 array of split-ring resonator (SRR) cells. The antenna is designed on cheap FR-4 dielectrics to work at 17.25 GHz. The antenna performances in terms of directivity and bandwidth have been improved about 5 dBi and 0.75 GHz, respectively. The simulations show that the antenna provides a few attractive features such as high gain, low-cost, low profile, easy to fabricate, which makes the design suitable for 5G systems.**

Keywords—5G antenna; FPC antenna; FR-4; Improved performamnce; PRS; SRR

I. Introduction

An increasing demand for radio spectrum has resulted from the growing high-data-rate wireless applications such as the fifth generation (5G) wireless systems [1]. One of the new features in 5G systems is the shift of operating frequencies to higher frequency bands (beyond 10 GHz). Increasing the operation frequency makes it easier to have broader bandwidths [2]. However, moving to the higher frequencies would lead to new challenges in the designs of antennas as well, which needs careful consideration [3].

Even though the microstrip antennas have attractive features such as low-profile, light-weight, small size, they also have some disadvantages such as low gain, low efficiency, narrow bandwidth [4]. The Fabry-Pérot cavity (FPC) antenna, which utilizes one or multiple partially reflecting surface (PRS) to enhance the radiation performance, has received extensive attention as a solution to this demand [5-6].

This study proposes a compact design of coaxial-fed FPC antenna with improved radiation performance for 5G communications. The design consists of a coaxial-fed patch antenna (basic structure), an air cavity, and also a PRS which is composed of 4×4 split-ting resonator (SRR) cells. The SRR is one of the most important metamaterial elements and have received great attention in the design of antennas. It usually consists of two concentric metallic rings with a split on opposite sides. It shows the resonant behavior at the wavelengths larger than its own size and could be harvested for energy/power [7-8]. The designed antenna is working in the frequency range of 16.5 to 18.5 GHz. The bandwidth, efficiency, realized gain and directivity characteristics of the proposed antenna are investigated.

This manuscript is structured as follows: The configuration of the proposed antenna has been described in Section II. Section III describes the fundamental characteristics of the coaxial-fed patch antenna. The investigation on the performance of the SRR unit cell has been done in Section IV. Section V discusses the simulation results of the final design. Finally, last Section concludes the presented study.

II. FPC Antenna Configuration

Firstly, a conventional patch antenna fed by a coaxial probe is designed. A PRS superstrate with a 4×4 array of SRR unit cells and with a distance of d_f above the patch antenna is employed for the proposed design. The distance between the main radiator and the PRS should be around λ/2 of the operation frequency. Both of the primary radiator and PRS structures are designed on FR-4 substrates with h=0.8, ε_r= 0.025, and δ=0.025. The proposed design has a compact size of $W_f \times L_f$=25×25 mm^2 and operates at 17.25 GHz (with more than 1.5 GHz impedance bandwidth). The parameter values of the conventional patch antenna, the final design and also its unit cells are listed in Table I.

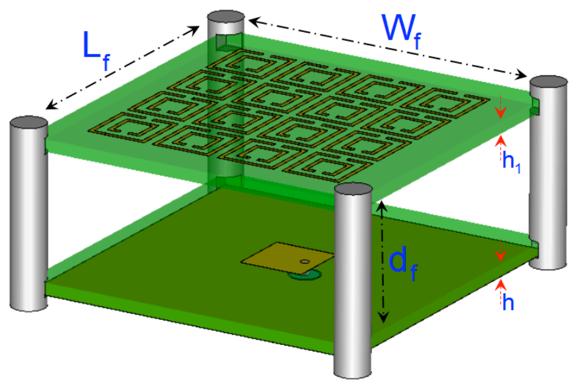


Fig. 1. 3D schematic of the proposed FPC antenna.

TABLE I. DIMENSION VALUES OF THE PROPOSED ANTENNA

Parameter	W_f=L_f	W	h=h_1	W_P	d_S	x
Value (mm)	25	8.5	0.8	3.75	1.7	0.625
Parameter	y	d	d_1	d_f	W_C	L_C
Value (mm)	1.625	0.5	1.72	9.7	5	10
Parameter	W_1	L_1	W_2	L_2	W_3	W_4
Value (mm)	3.5	3.5	1.5	2	0.25	0.5

III. LOW-PROFILE COAXIAL-FED PATCH ANTENNA

The schematic of the single element 17.25 GHz patch antenna is shown in Fig. 2. As illustrated, the antenna is fed by a 50-Ohm coaxial probe form backside. The inner and out conductors of the coaxial cable have diameters of d=0.5 mm and d_1=1.72 mm, respectively. The antenna has a square radiation patch with length of W_P. The operation frequency of the patch antenna is inversely proportional to the length of its main radiator and can be configured by changing the antenna parameters. Figure 3 illustrates the simulated reflection coefficient characteristic of the antenna. As illustrated, the antenna covers the frequency band of 16.5-18 GHz.

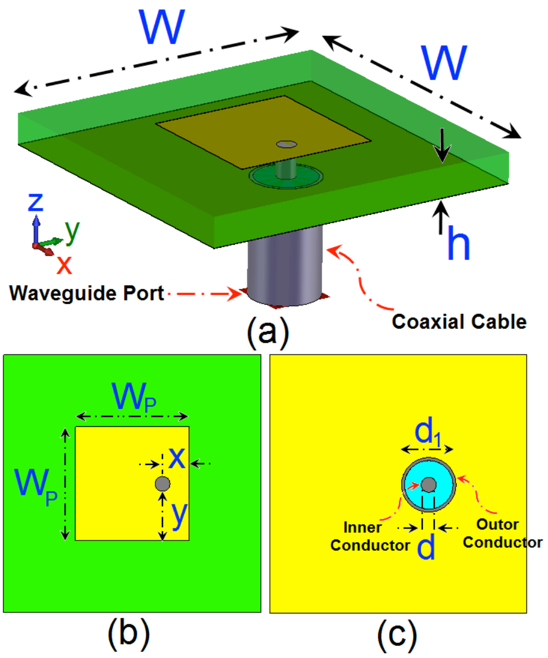


Fig. 2. (a) Side, (b) top, and (c) bottom views of the antenna.

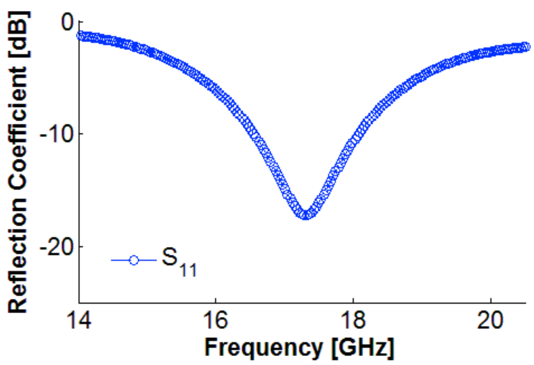


Fig. 3. Simulated reflection coefficient (S_{11}) of the patch antenna.

The 3D radiation pattern of the antenna at 17.25 GHz is illustrated in Fig. 4. As seen, the antenna has a good radiation behavior with 4.86 dB realized gain and low back-lobe at the resonance frequency. It can be observed in Fig. 5 that the antenna has sufficient radiation and total efficiencies and also 5 dBi directivity at the frequency range of 16.5-18 GHz.

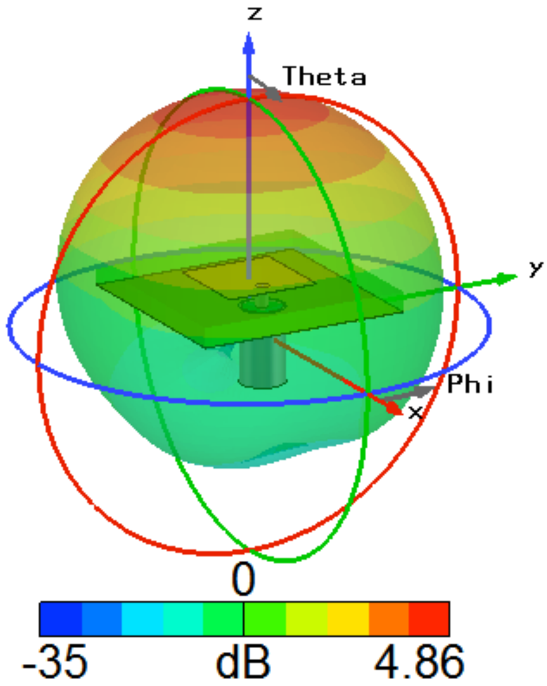


Fig. 4. Transparent 3D view of the antenna radiation pattern at the center frequency (17.25 GHz).

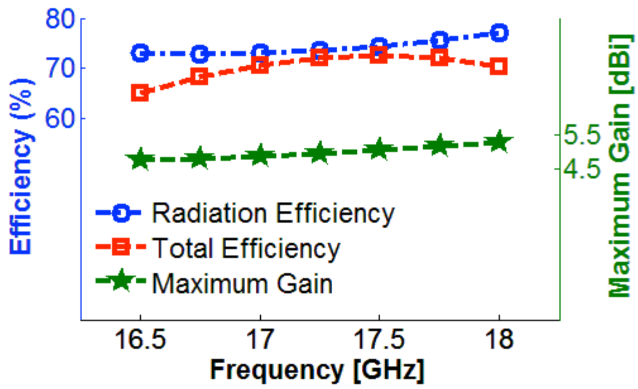


Fig. 5. Simulated radiation characteristics of the antenna over the antenna operation frequency range.

IV. SRR UNIT CELL

The radiation behavior of the Fabry antennas depends on the performance of the unit cells used in the PRS and needs careful consideration. Figure 6 shows the configuration of the unit cell which is a metallic SRR on the same layer of FR-4 substrate. In the Fabry antennas, in order to transmit all energy through the cavity without reflection, the difference between S_{11} and S_{21} characteristics of the unit cells at the operation frequency range must be maximum ($|S_{11}|>|S_{21}|$) [9].

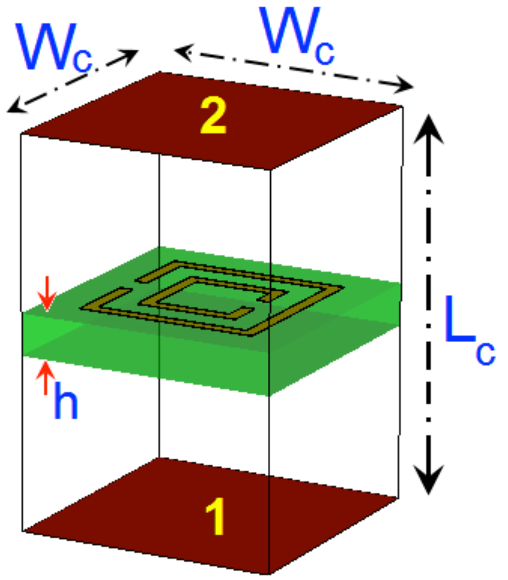


Fig. 6. Configuration of the designed SRR unit cell.

Figure 7 displays the S parameters (S_{11} and S_{21} in linear) of the designed SRR. As shown, the proposed SRR unit cell has a good performance in the frequency range of the designed patch antenna.

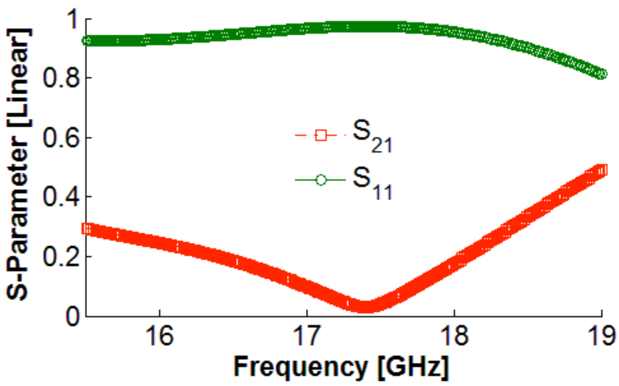


Fig. 7. S-parameters of the SRR unit cell.

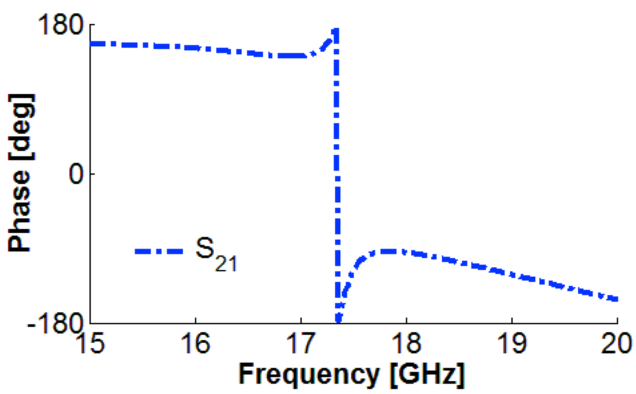
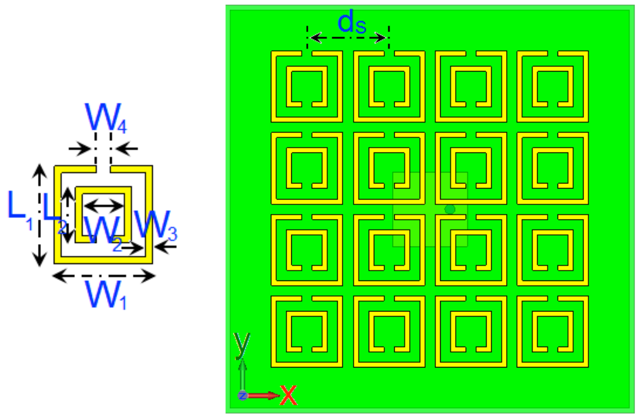


Fig. 8. S_{21} (in phase) of the SRR unit cell versus frequency.

In addition, the S_{21} (in phase) characteristic of the unit cell shown in Fig. 8, validates the sufficient behavior of the SRR in the frequency range of 16.5 to 18 GHz. The parameters of the SRR are specified in Fig. 9 (a). As mentioned in Section. II, a 4×4 array of the proposed SRR unit cells with a distance of d_S have been used to form the superstrate above the patch antenna. Figure 9 (b) displays its configuration.



(a) (b)

Fig. 9. Configurations of the (a) SRR, and (b) PRS.

V. Radiation Behaviour of the Proposed Antenna

In this Section, the properties of the designed FPC antenna (final design) in terms of input-impedance, directivity, and antenna-gain have been investigated. The side view of the proposed FPC antenna (consists of the coaxial-fed patch antenna, an air cavity, and the PRS superstarte) is displayed in Fig. 10.

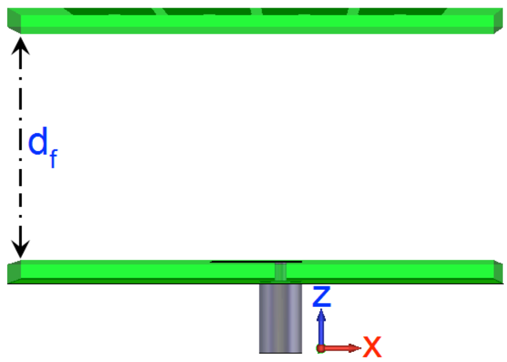


Fig. 10. Side view of the designed FRC antenna.

Figure 11 illustrates the simulated results of the antenna reflection coefficient w/wo PRS superstare (patch antenna and the proposed FPC antenna). As can be seen, both of the antennas have good frequency responses in the band of 16.5 to 18 GHz. However, the proposed Fabry antenna has a wide bandwidth with good impedance matching compared with primary coaxial-fed radiator (patch antenna with an extended ground plane). It can be observed that using the Fabry superstarte has enhanced the bandwidth of the patch antenna.

In order to demonstrate the effect of the Fabry superstare on the performance of the main radiator, the current distribution of the final design at 17.25 GHz (resonance frequency) is illustrated in Fig. 12.

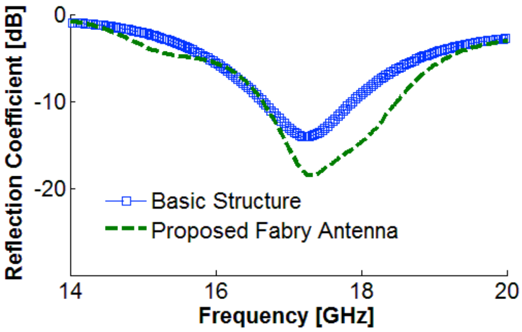


Fig. 11. Comparison between the reflection coefficient (S_{11}) characteristics of the basic patch antenna and the proposed design.

It can be clearly seen that the current flows are distrubuted around the main radiator and also the SRR unit cells of the PRS. The superstrate has a focusing impact on the distribution of fields in the cavity and can increase the effective aperture area, which leads to the improvement of the antenna radiation performance [6].

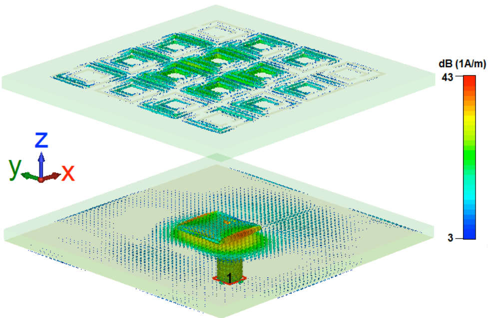


Fig. 12. Current distribution of the designed Fabry antenna at 17.25 GHz.

3D radiation patterns of the proposed FPC antenna at 17, 17.5, and 18 GHz have been illustrated in Fig. 13. As seen, the antenna has more than 10.4, 10.8, and 11.3 dBi directivities, respectively. In addition, the realized gain values of the antenna at these frequencies are 8.04, 9.9, and 10.4 dB. The antenna provides good efficiencies (70%~80%), even though it has been designed on the high loss FR-4 dielectrics to work at higher frequencies.

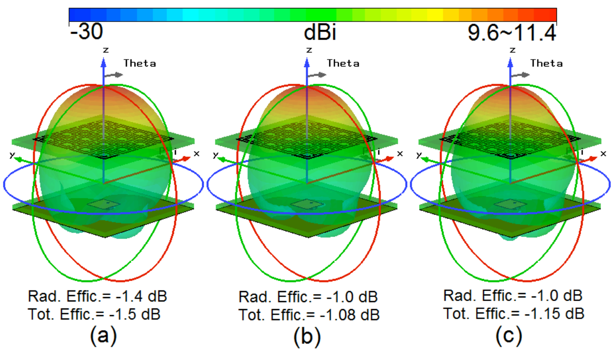


Fig. 13. 3D radiation patterns of the Fabry antenna at, (a) 17 GHz, 17.5 GHz, and 18 GHz.

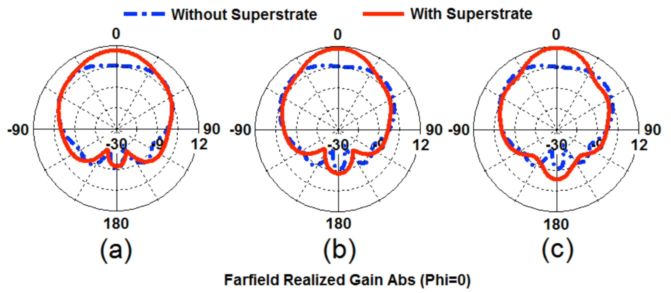


Fig. 14. 2D polar radiation patterns of the antenna w/wo superstarte at (a) 17 GHz, (b) 17.5 GHz, and (c) 18 GHz.

2D-polar radiation characteristics of the designed antenna w/wo superstrate at different frequencies of the antenna bandwidth have been displayed in Fig. 14. As shown, it can be observed that significant improvement on the antenna performance using the Fabry-superstarte has been achieved. On the other hand, the radiation patterns of the Fabry antenna are more directional compared with basic structure.

VI. Conclusion

A compact Fabry-Pérot cavity antenna for use in 5G systems is proposed in this study. The antenna is composed of a conventional patch radiator, an air cavity, and also PRS superstare with SRR cells. FR-4 dielectrics have been used as substrate and superstrate. Using the Fabry design, the performances of the antenna in terms of different fundamental radiation characteristics have been improved. The antenna also features a wide impedance bandwidth > 2 GHz (16.5-18.5 GHz). The efficiency of the antenna varies form 70% to 80% at its operation bandwidth.

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