Design of Differential-Fed Filtering Patch Antenna with High-Gain and Dual-Polarized Characteristics for 5G Systems

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Abstract. In this paper, a new high-gain differential-fed dual-polarized microstrip filtering antenna with high common-mode rejection is presented. Two differential pairs of probe feeding ports are utilized to provide differentially exciting signals. The filtering response is achieved by introducing four symmetrical open-loop ring resonator slots on the top layer surrounding the four excitation ports of the patch antenna. The resonators can produce nulls at the low edge of the passband bandwidth with high gain and wide stopband characteristics. Because of the strictly symmetric configuration of the proposed antenna, the design is studied and analyzed only in one polarization configuration. Compared with other presented filtering antenna designs, the proposed design has not only high gain and dual-polarized characteristics but also introduces high efficiency and much lower cross-polarization level due to the differentially driven ports. The filtering antenna is designed, simulated and optimized using computer simulation technology (CST) software using a Rogers TMM3 substrate with a relative dielectric constant of 3.45. Also, the antenna has a single layer substrate with a height of 0.035 of the free space wavelength and operating at 3.54 GHz for 5G communications.

Keywords: Filtering antenna, CST, differentially-fed, Dual-Polarized, high-gain, microstrip.

1 Introduction

As indicated by the office of communication (Ofcom), sub 6 GHz (3.4–3.8 GHz) spectrum has been allocated for fifth generation (5G) and many modern microwaves (MW) and radio frequency (RF) components such as antennas, filters and power amplifiers [1-25]. Thus, microstrip antennas with filtering performance, high gain, high isolation, high front-to-back ratio (FTBR), stable radiation pattern, good common-mode (CM) rejection level and unidirectional radiation pattern in the planar configuration simultaneously are necessary for 5G applications [26-31]. Recently, dual-polarized and differential-fed techniques have been extensively introduced to improve the performance of the microwave and RF systems [32-34]. Different differential-fed antennas have been reported, such as planar antennas [35-38], magneto-electric dipole antennas [39, 40], 3D-backed antennas [41], and so on. A differential

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planar antenna presented in [35] is fed by 0^0 and 180^0 signals, providing low cross-polarization, wide bandwidths, and high gain. The presented design has a bandwidth of 13 GHz and resonates at 13.2 GHz for Ku-band wireless applications. Unlike conventional differentially fed microstrip antennas, the designs proposed in [36] and [37] employ a folded plate pair as the differential feeding approach. The proposed antennas have stable realized gains around 8 dB within the operating bandwidth, providing high stability of the radiation patterns with the symmetrical performance for the two resonating modes. A differential-fed planar antenna with a realized gain of 8.2 dBi and a 130 MHz bandwidth is presented in [38]. The designed antenna can serve different applications such as energy harvesting, Radio-frequency identification (RFID) tags and differential/balanced circuits.

The above-mentioned differential-fed microstrip antennas operating with a single polarization radiation pattern. Dual-polarized antennas provide polarization diversities to decrease the side effect of multipath fading or improve channel capacity are presented in [42]. They find prospective application in many wireless communications, especially in base stations of cellular mobile phones. Nevertheless, there are few researchers proposed differential-fed dual-polarized microstrip antennas [43, 44]. In [43], a dual-polarized cavity-backed planar antenna with differentially driven coaxial feeds is introduced. In this antenna, both polarizations can be tuned from 0.65 GHz to 1.2 GHz using (1.2–5.4 pF) varactor diodes. Besides, the fractional bandwidth differs from 1% to 2% over that range.

In this work, a new differentially fed, dual-polarized, and high gain filtering antenna is designed, simulated and implemented. Four half-wavelength open-ring slots are loaded to the radiating patch as resonator filters to provide the filtering characteristics. The filtering antenna is designed on a Rogers TMM3 substrate with a relative dielectric constant of 3.45, loss tangent = 0.002 and thickness h = 3.2 mm, and is simulated and optimized using finite element solver software (CST) simulator. Because of the differentially-driven and strict symmetrical geometry, very good performance including high stability of the radiation pattern characteristics, high isolation, good CM rejection, low-cross polarization level with filtering characteristics are obtained. All of these merits make the presented microstrip antenna suitable for the sub-6GHz 5G communications. The proposed dual-polarized filtering antenna is fabricated and measured, and good agreement is achieved between the simulated and measured results.

2 Differentially fed filtering patch antenna design and configuration

The geometry of the proposed dual-polarized differentially driven microstrip filtering antenna is shown in Fig. 1. The filtering antenna is designed on a Rogers TMM3 substrate with a relative dielectric constant of 3.45, loss tangent = 0.002, and thickness h = 3.2 mm. The proposed filtering antenna composites of circular dick radiating patch four metallic shorting vias and two pairs of differential feeding probes. The differentially fed port 1 is composed of port 1+ and port 1−, whereas the differential-fed port 2 is composed of port 2+ and port 2−. Adding slots with different shapes to the radiating patch can affect the surface current densities or excite specific frequency modes. Therefore, the antenna size can be reduced with improved performance. In our paper, the slots are loaded on the antennas to provide a broadside radiation-pattern nulls at the upper edge of the in-band antenna frequency response, providing filtering response with wide stopband rejection. The presented antenna consists of four open-loop ring slots, which are loaded on the top layer of the radiating patch. The total length of each slot is about half the wavelength of the resonant frequency. CST software is used for analyses and simulations to obtain optimal design configuration. As the initial parameters of the CST simulator, the actual radius of the patch (R) at the resonant frequency f_0 can be calculated as [45]

$$R_e = R\left\{1 + \frac{2h}{\pi\varepsilon_r h}\left[\ln\left(\frac{\pi R}{2h}\right) + 1.7726\right]\right\}^{1/2}$$

Where h and ε_r represent the height and permittivity of the substrate, respectively.

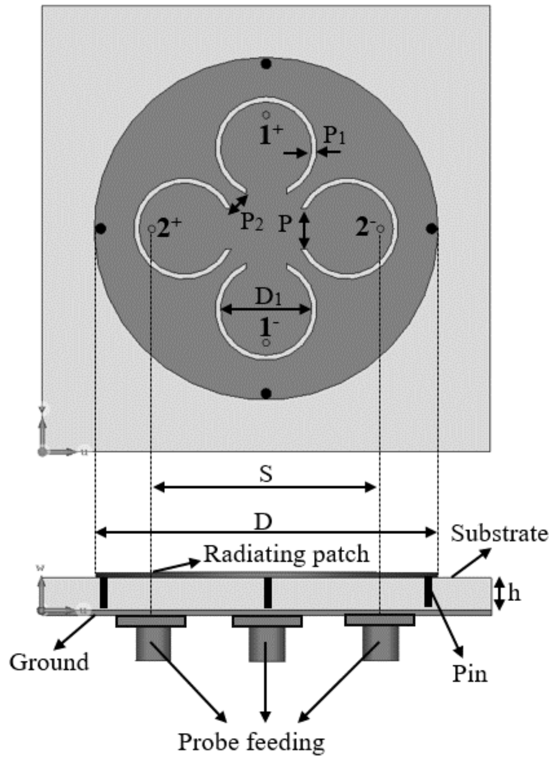

Fig. 1. Top- and side- view of the introduced differentially fed design.

In this work, CST software is used for analyses and simulations to obtain optimal design configurations. Table 1 summarizes the final optimized dimensions of the proposed high-gain differential-fed dual-polarized filtering microstrip antenna. The simulated current distributions of the proposed filtering antenna at differential port 1 and port 2 excitations at the resonant frequency are illustrated in Fig. 2.

Table 1. Dimensions of the proposed filtering microstrip antenna.

Parameters	D	D_1	S	P	P_1	P_2	h
Values (mm)	29	7.5	20	4	0.5	2	3.2

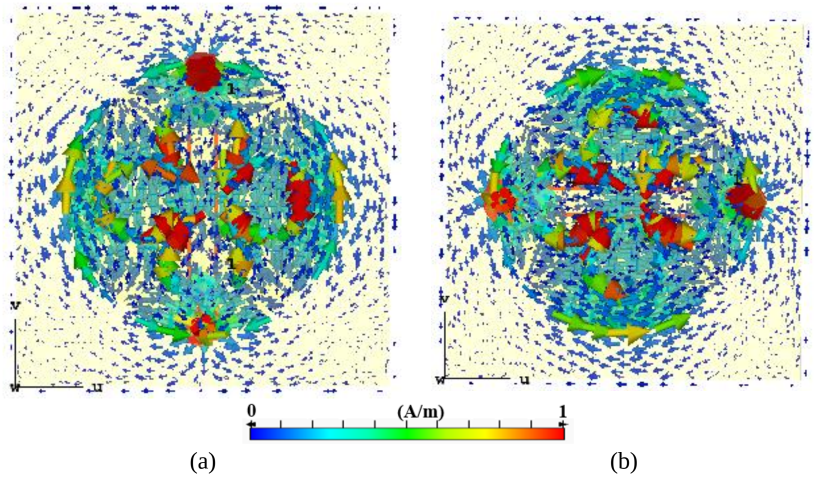

Fig. 2. The current distribution of the introduced differentially fed structure at 3.54 GHz. (a) Feeding port 1. (b) Feeding port 2.

By feeding differential port 1 only, the current density is concentrated on the longitudinal axis around the two ports (port 1+ and port 1−). On the other hand, by exciting differential port 2 only, the current density is concentrated on the transverse axis around the two ports (port 2+ and port 2−), and thus, providing two orthogonal polarizations.

3 Filtering patch antenna performance

In this section, filtering antenna characteristics in terms of reflection coefficient, peak realized gain, efficiency, and radiation pattern are presented and discussed. As long as the proposed patch antenna has a strict symmetry configuration, therefore the characteristics in only one polarization scenario (port 1^+ and port 1^-) are studied to show the filtering performance of the antenna, while the performance will be identical on the second state. Figs. 3 and 4 show the differential reflection coefficients of the presented filtering antenna. The obtained performance illustrates that the filtering antenna resonances at the sub-6 GHz 3.54 GHz. The performance shows that the filtering antenna has less than -25 dB reflection coefficient at resonance, with a fractional bandwidth of 2% (see Fig. 3). Besides, and under exciting the two differential ports, the isolation between the two ports is plotted in Fig. 4. Good polarization isolation, greater than 65 dB, is obtained between the two differential ports.

The total simulated efficiency for the presented dual-polarized antenna is illustrated in Fig. 5, it can be shown that the total efficiency is greater than 80% through the operating bandwidth, whereas it is less than 10% through the stopband spectrum. Next, the far-field normalized radiation patterns are simulated and presented under the excitation of the differential-fed port 1 (port 1+ and port 1-). The radiation patterns are simulated in the xz- and yz- planes at the resonant frequency (see Fig. 6). In the xz-plane, the achieved cross-polarization (x-pol) level is calculated to be 85 dB lower than the corresponding value of the achieved copolarization (Co-pol) level. On the other hand, in the yz-plane, the achieved cross-polarization (x-pol) level is calculated to be 70 dB lower than the corresponding value of the achieved copolarization (Co-pol) level.

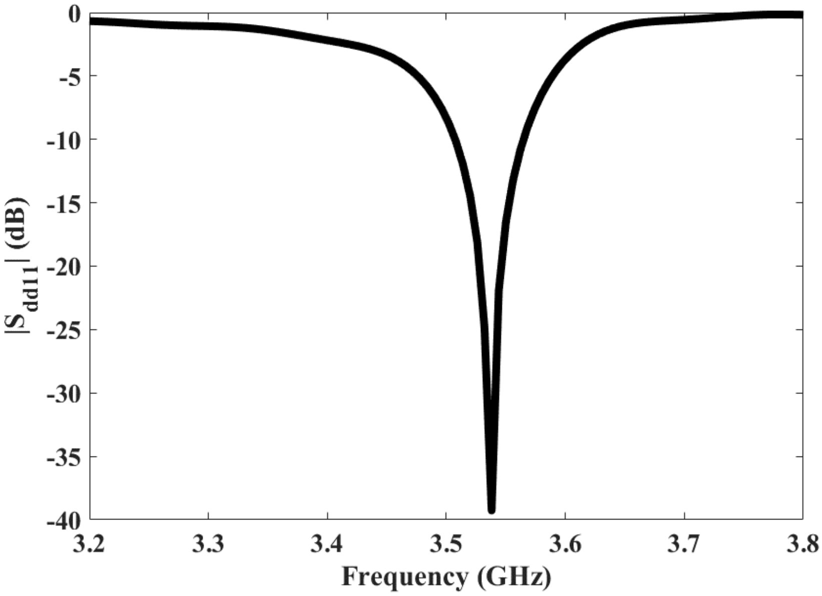

Fig. 3. |Sdd11| results of the proposed differential-fed dual-polarized microstrip filtering antenna.

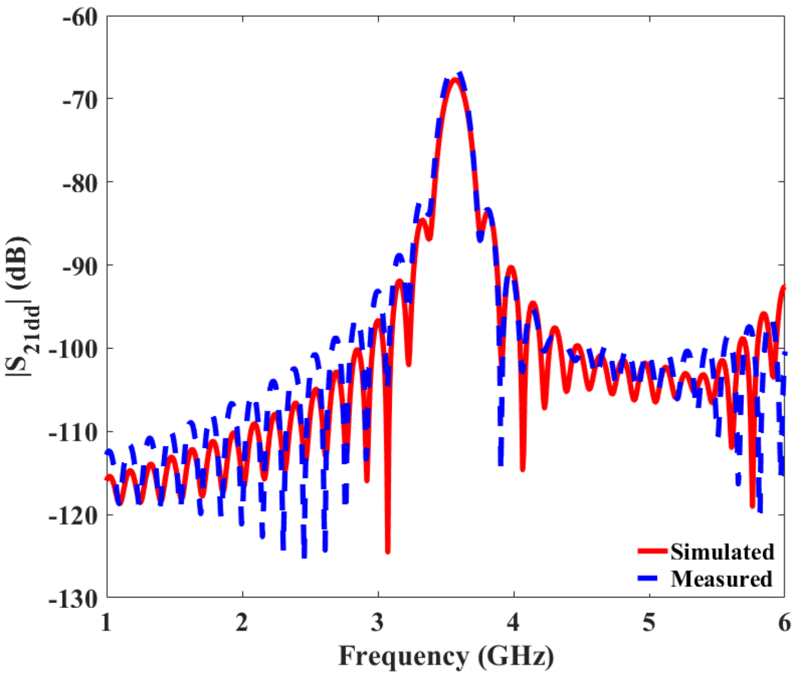

Fig. 4. |Sdd$_{12}$| results of the proposed differential-fed dual-polarized microstrip antenna.

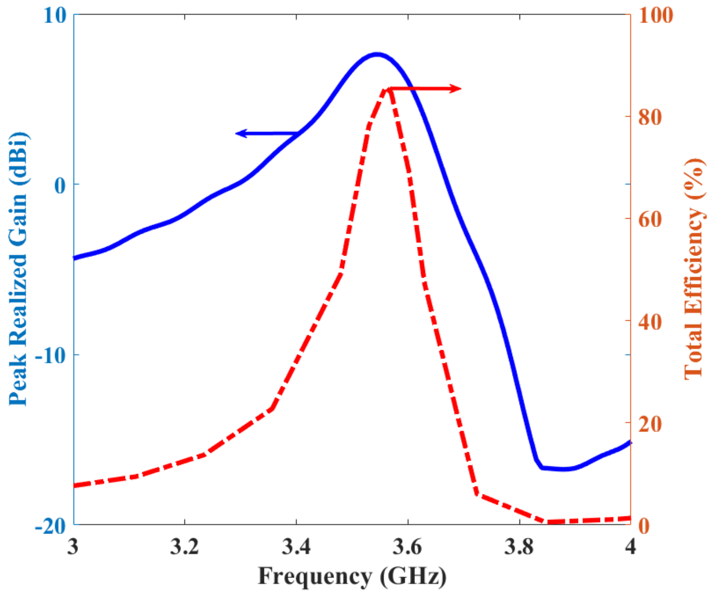

Fig. 5. The total efficiency and gain of the proposed differential -fed microstrip filtering antenna.

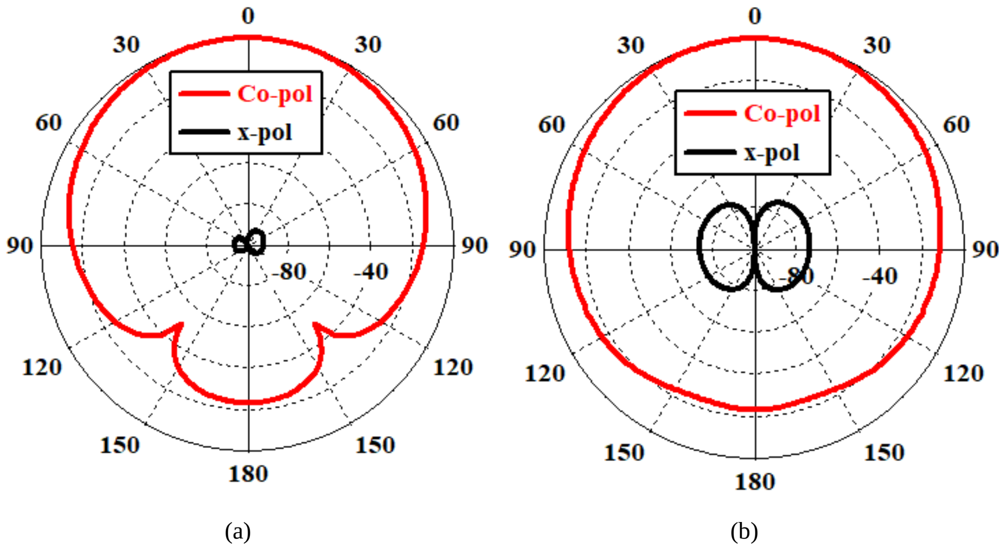

Fig. 6. Far-field radiation patterns at the resonant frequency for differential port 1 excitation of the proposed antenna. (a) xz-plane. (b) yz-plane.

4 Conclusions

In this manuscript, a new differential-fed dual-polarized filtering patch antenna with high gain and high common-mode rejection is presented. Filtering performance is achieved by etching a symmetrical open-loop ring resonator filter to the top layer of the radiating patch. Good performance is achieved at the resonant frequency of 3.54 GHz with a realized gain of more than 7.5 dBi around the passband. Furthermore, the performance has exhibited a few attractive features of our presented filtering antenna, that is, high gain, high efficiency, as well as much lower cross-polarization level due to the differentially-driven ports, and complete symmetry of the configuration. The antenna is dual polarized with a height of 0.035 λ_g and operating at the sub-6 GHz 5G spectrum. The designed antenna is simulated and optimized using the CST.

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