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Design of Radiation Pattern-Reconfigurable 60-GHz Antenna for 5G Applications

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Abstract— Reconfigurable beam steering using circular disc microstrip patch antenna with a ring slot is proposed. The overall dimension of the antenna is 5.4×5.4 mm^2 printed on a 0.504 mm thick, Rogers RT5870 substrate with relative permittivity 2.3 and loss tangent 0.0012. The designed antenna operates at the expected 5G frequency band 60 GHz with a central coaxial probe feed. Two NMOS switches are configured to generate three different beam patterns. Activating each switch individually results in a near 70^o shift in the main beam direction, whereas the frequency characteristics are unchanged. The power gains are between 3.9 dB and 4.8dB for the three states of switches configurations. Simulated results in terms of return loss, peak gains and radiation pattern are presented and show a reasonable agreement at the expected 60 GHz band for 5G applications.

Index Terms—Beam Steering, 5G Antennas, Microstrip Antennas, NMOS, Reconfigurable Antennas

1 INTRODUCTION

Idealy, reconfigurable antennas must be able to change their operating frequency, polarization and radiation pattern independently to provide varying operating requirements [1]. Moreover, the progress of these antennas faces important challenges to both antennas and system designer. However, these challenges will come not only from the antenna design, but also from the surrounding technologies that enable reconfigurability [2], [3].

Now days, there exist an extensive research areas covering reconfigurable antennas usually concerned on the design and the technological perspectives. Radiation patterns and polarization reconfigurable antennas are also very useful because they can present variety characteristics which lead to an improvement signal to noise ratio (SNR) as well as higher quality of service (QoS) of the whole systems.

Newly, theoretical and measurement results of a 5G communications devices operating at mmWave was studied and discussed in [4]. Other researchers presented and studied the unprecedented hardware challenges and essential design considerations concerned on the antenna system methodology for future 5G communication devices [5]. The designed antenna in [5] able to achieve good effective isotropic radiated power with minimum power consumption for practical deployment of 5G cellular communications.

In modern wireless communications systems like 5G application, antennas may be necessary to have different direction of the main beams and one of the methods to achieve this property is by using several single antenna elements in an array to achieve pattern diversity [6]. The pattern diversity of an array may be diverse by setting the so called array factor [7]. However, mutual coupling between antenna elements in an array antenna has significant effects on wireless radio links, causing undesirable effects on system performance. One efficient method to limit these drawbacks is a reconfigurable antenna.

Radiation pattern reconfigurable antennas are able to diverse the main lobe direction or null direction at a specific angles. By the way, it may provide wider coverage by redirecting the main lobe and avoiding interference of noise signals by controlling the main beam locations.

Generally, PIN diodes [8], [9], [10] and RF-MEMS [11], [12] are used as switching elements in order to alter the antenna radiation patterns. In [9], pattern and frequency reconfigurable annular slot antenna was presented. Matching stubs are used to match the antenna to three different frequencies, 5.2, 6.4 and 5.8 GHz. PIN diodes are used as switches to activate or deactivate the stubs creating a reconfigurable matching network. In [12], the author explained the integration of the radio frequency microelectromechanical system (RF MEMS) switches with radiation pattern reconfigurable antennas. In another design [13], a radiation pattern switchable parasitic array antenna at 60 GHz band was studied. NMOS transistor switches are used to alter the main beam direction of the antenna with constant frequency. The beam switching of this antenna can deviates at $\pm 56^0$.

The work presented here introduces a new pattern-reconfigurable planar circular disk microstrip antenna capable to control the main beam direction using two NMOS switches. The design investigations initiate from a conventional disk antenna with a ring slot. The operational configurations are achieved through independently controllable switches, in which each one of them is implemented as an NMOS. The designed antenna alters the radiation pattern according to the three switch combinations which can alternate the main beam into three states of patterns. The proposed antenna is printed on the top of a 0.504 mm thickness of Rogers RT5870 substrate with relative permittivity 2.3 and loss tangent 0.0012 of size 5.4×5.4 mm^2.

The proposed antenna delivers multiple radiation patterns at a single frequency. The radiation pattern direction of the designed antenna deviates about 70^O in yz- plane at 60 GHz frequency. CST studio simulation software based on a finite integration technique (FIT) [14] is used to optimize the antenna design structure.

2 Antenna Structure

Fig. 1 shows the schematic diagram of the proposed antenna. An annular slot ring circular disk planer antenna is designed. The feeding network used here is a coaxial probe with connecting radius equal to 0.07mm. The circular disk has an outer radius R_1=1.85 mm and the inner radius R_2=0.91 mm. Detailed dimensions of the proposed antenna are shown in Table 1. The dimensions of this antenna are optimized to operate in the resonance frequency 60 GHz covering 2GHz bandwidth with a return loss less than 10dB.

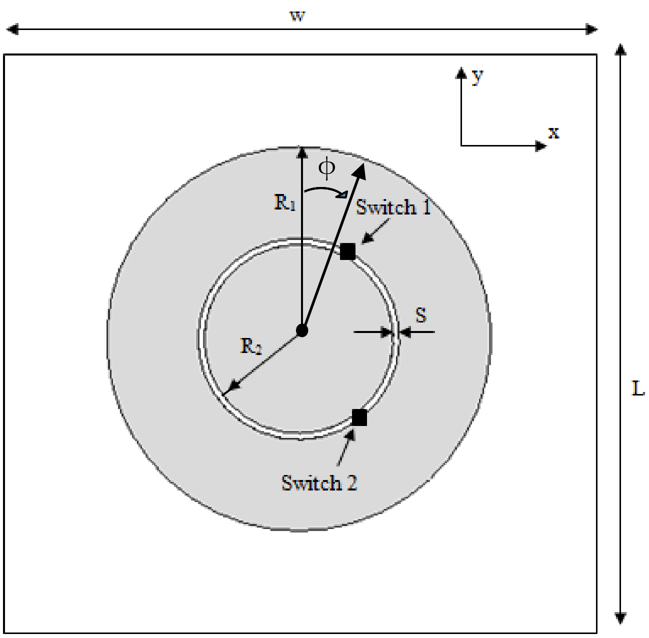

Figure 1: The geometry structure of the proposed antenna.

TABLE 1
Detailed Dimensions of Designed Antenna shown in Figure 1

W (mm)	L (mm)	S (mm)	R_1 (mm)	R_2 (mm)
5.4	5.4	0.06	1.85	0.91

3 Parametric Study

In this section, the influences of various positions of the switches on both the response and radiation pattern of the designed antennas are discussed. Firstly the switches are modeled as metal tab that is represented the ideal state of the switches. The metal tab is rotated along the slot ring of the antenna by an angle φ (φ= 0^0, 30^0, 150^0, 180^0). And both the return loss and radiation pattern are observed. Fig. 2 shows the simulated reflection coefficient as function of frequency for various sweep angles of φ. As the position of the switch is shifted, the resonance frequency of the antenna shifts slightly around 60 GHz. In fact this frequency shifting can be neglected since the resonance bandwidth around 60GHz is stayed unaffected. On the other hand the effect of the parameter sweep on the radiation pattern in the yz- plane is studied and presented in Fig. 3. It is clear that the reconfigurable property is achieved at two important and symmetrical angles (φ= 30^0 and 150^0) along yz-plane.

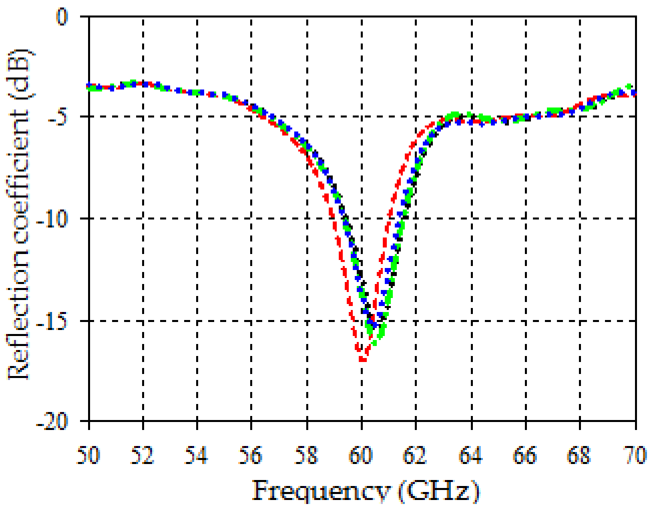

Figure 2: The frequency response of the input reflection coefficient for different angles of φ using the metal tab as switch (φ=0: dotted line, φ =30: solid line, φ=150: dashed line and φ=180: dotted/dashed line).

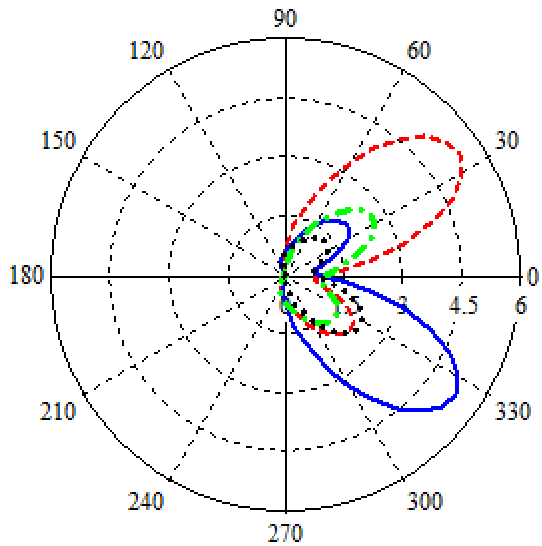

Figure 3: Radiation pattern at yz-plane for different angles of φ using the metal tab as switch (φ=0: dotted line, φ =30: solid line, φ=150: dashed line and φ=180: dotted/dashed line).

Latterly, two NMOS transistor are used as switches to replace the metal tab, in which switch 1 is located at position shifted by (φ = 30^0) from the y-axis, whenever the switch 2 is then shifted by (φ = 150^0) from y-axis. It should be noted that within the computer simulation technology (CST), the NMOS transistor switches are modeled with a lumped element network with R_{on}= 10.2 Ω, C_{on}= 47.1 pF, R_{off}= 13.3 MΩ, C_{off}= 39 pF as shown in Figure 4. The figure shows the equivalent circuit for the switches in the ON and OFF states.

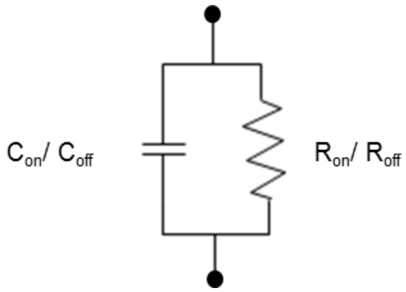

Figure 4: Simplified electrical model of the NMOS transistor switch in ON and OFF states.

4 Simulation Results

The performances of the proposed antenna, in terms of return losses, radiation patterns, efficiencies and gains, with different states of switches have been studied as follows

4.1 Impedance Bandwidth

Fig. 5 shows the simulated results for the above designed antenna. It is clear that (SW1 ON, SW2 OFF) state has -18 dB reflection coefficients at resonance frequency 60 GHz with impedance bandwidth 3.4% at S_{11} < -10 dB. In (SW1 OFF, SW2 ON) state, the reflection coefficient is -16 dB at 61 GHz resonance frequency, with corresponding impedance bandwidth 3.3%. Whenever, in (SW1 ON, SW2 ON) state, S_{11} is equal to -30 dB at 60.8 GHz resonance frequency, with impedance bandwidth 5.7%.

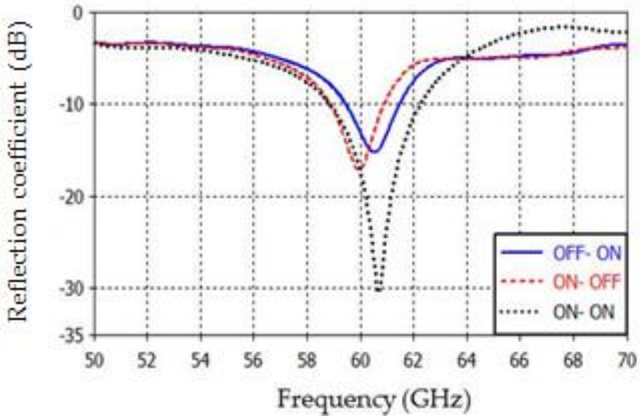

Figure 5: Simulation results for the proposed antenna for different states of switching.

The main difficulty of the radiation pattern reconfigurable antenna design is that this type of reconfigurability must be accomplished without significant changes in the impedance or frequency characteristics. The achieved results overcome this difficulty by making the single resonance frequency for all the states of switches.

4.2 Radiation Patterns and Directivities

Figs. 6, 7 and 8 show the simulated radiation patterns at 60 GHz in the yz-plane (E-plane). When the proposed antenna operates at (SW1 ON, SW2 OFF) state, the beam's maximal direction in the yz-plane is 35^0. At (SW1 OFF, SW2 ON) state, the beam's maximal direction in the yz-plane is -35^0. At (SW1 ON, SW2 ON) state, the beam's maximal direction in the yz-plane in (35^0, -35^0). "+" indicates that the radiation pattern tilts toward the positive y axis and "-" indicates that the radiation pattern tilts toward the negative y axis.

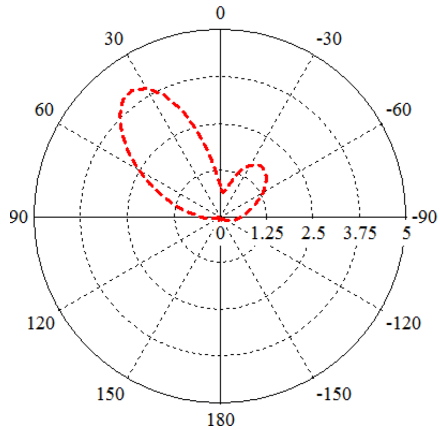

Figure 6: Radiation pattern at yz-plane in the on-off state

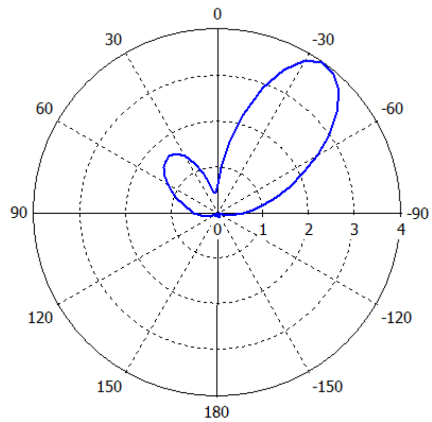

Figure 7: The radiation pattern at yz-plane in the off-on state.

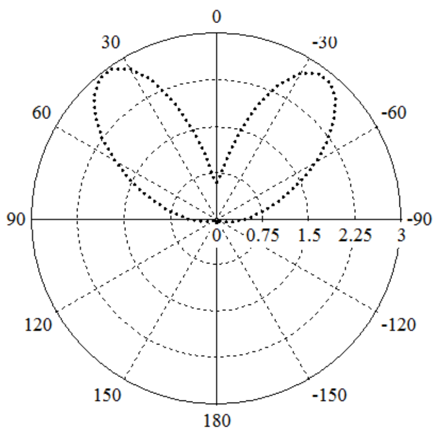

Figure 8: Radiation pattern at yz-plane in the on-on state

According to the above results, the radiation patterns of the proposed antenna operating at different switching states can divers by 70⁰ shifted along yz-plane (E-Plane).

Due to the symmetry characteristics on both the antenna structure and switches positions, the single main beam direction can be altered symmetrically around the z axis in the yz-plane as shown in Figs. 6, 7 and 8. Figs. 9, 10 and 11 show the 3D simulation results for beam directivities which correspond to the cases of switching in both ON and OFF states.

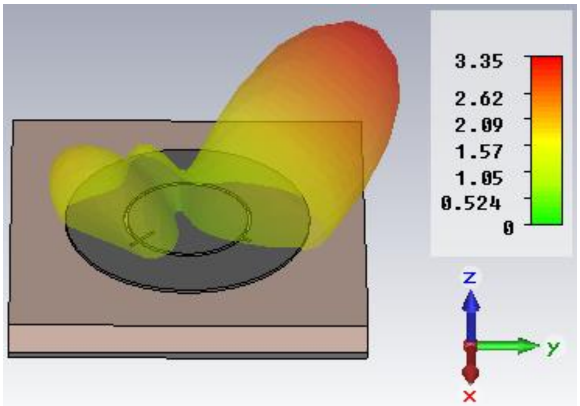

Figure 9: 3D radiation pattern in the on-off state.

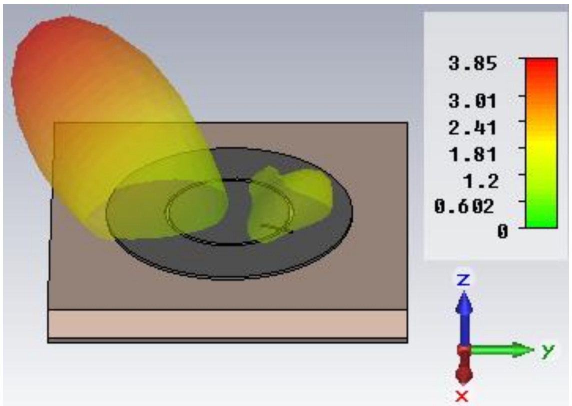

Fig. 10. 3D radiation pattern in the off-on state

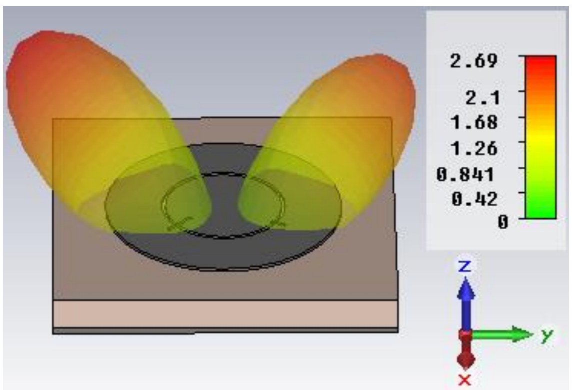

Figure 11: 3D radiation pattern in the on-on state.

4.3 Antenna Gains

Simulation results for the gains of the radiations as a function of frequency are shown in Fig. 12. Simulated maximum gain at (SW1 ON, SW2 OFF) is 4.5 dB. At (SW1 OFF, SW2 ON) state, the maximum gain is 4.8 dB. And at (SW1 ON, SW2 ON) state, the maximum gain and directivity are 3.9 dB.

4.4 Total Efficiency

Total efficiency for the designed antenna is studied and plotted as function of frequency in the useful bandwidth of 60 GHz as shown in Fig. 13 at different state of each switch. It is clear that the achieved efficiencies are better than 95% at all the states of switches.

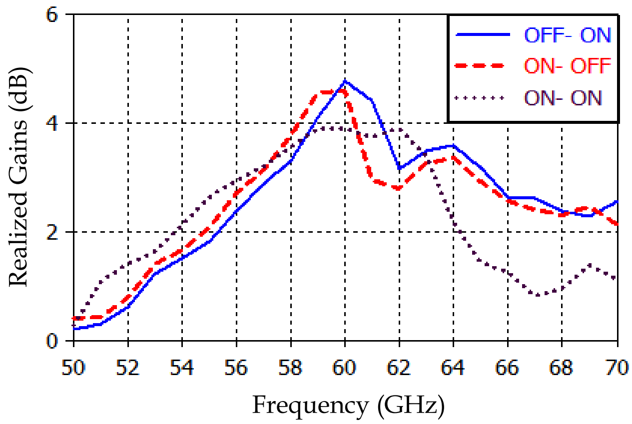

Figure 12: Realized gain in different states of switches for the proposed antenna

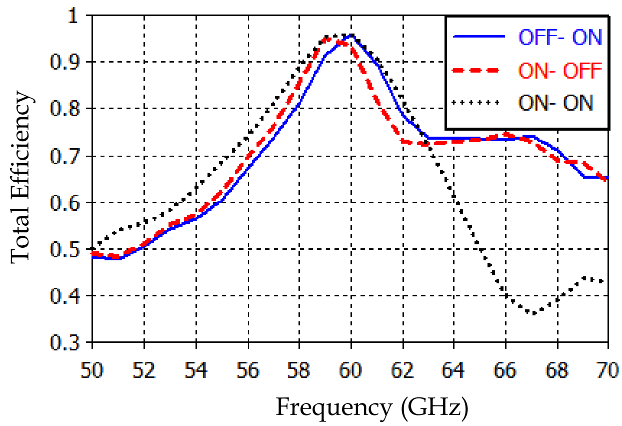

Figure 13: Total efficiency in different states of switches for the proposed antenna

5 Conclusion

A new design for pattern reconfigurable circular disk antenna loaded with an annular slot ring and operated at 60GHz has been presented. The antenna can switch between three different radiation patterns by employing two NMOS transistor. The achieved results show that the proposed antenna can redirect the main beam at -35⁰ and 35⁰ in the yz- plane with the maximum achieved gains are 4.5 dB, 4.8 dB and 3.9 dB with impedance bandwidths about 3.4%, 3.3% and 5.7% at resonance frequency 60 GHz in the (SW1 ON, SW2 OFF), (SW1 OFF, SW2 ON) and (SW1 ON, SW2 ON) states, respectively. Antenna efficiencies were achieved with values better than 95% in the three states of switching configurations. The antenna beam pattern characteristics, efficiencies, peak gains and impedance bandwidths are suitable for 5G applications. In addition, Due to the simple construction and beam pattern diversity, the designed antenna can find different applications in MIMO systems.

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