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Dual-polarized Patch Antenna of Large Frequency Tuning Range at mm-Wave Frequency Bands

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Abstract—In this paper, we present a dual-polarized frequency-reconfigurable patch antenna working at millimeter wave frequency bands for 5G applications. A square patch is surrounded by four metallic L-shaped walls. Four ideal varactor diodes are placed between the corners of the square patch and L-shaped walls. Frequency tunability is achieved by adjusting the capacitances of the varactor diodes. Two 50-Ω probes are used to feed the square patch which can excite two orthogonal polarizations. Operating frequency can vary from 23 GHz to 45 GHz with a 10-dB return loss when the capacitance decreases from 0.05 pF to 0.005 pF. The isolation between two polarizations is better than 13 dB over the operating frequency bands. Cross-polarization level is lower than –15 dB. In addition, the quality factor of varactor diodes is studied to demonstrate its influence on antenna efficiency.

Index Terms—5G, mm-Wave, frequency reconfigurable, dual polarized patch antenna, varactor diode.

I. INTRODUCTION

In the past, a new mobile communications generation has been established approximately every decade, and currently 5G (5th generation) networks are being adopted globally. An obvious difference of the 5G technology is that mm-Wave spectrum is used in addition to the sub-6 GHz frequencies. According to the Third-Generation Partnership Project (3GPP) definition, five frequency bands n257, n258, n259, n260, and n261 (from 24 to 43.5 GHz) have been assigned to the mobile communications. The wide bandwidth has many advantages such as the large channel capacity. However, it also calls for wide-band antennas challenging antenna design.

In [1], a vertical polarized magneto-electric (ME) monopole antenna is proposed. Low profile is achieved with top-loading, and mm-Wave bands from 23.5 to 44 GHz are covered. However, it is difficult to achieve that large bandwidth in a limited space. Therefore, many works still concentrate only on low bands from 24 to 29.5 GHz [2], [3]. The design challenge can be possibly mitigated by using reconfigurable antennas, whose instantaneously narrower band can be shifted in frequency. Furthermore, reconfigurable antennas might provide less frequency-dependent radiation patterns and help to avoid mutual interference between different frequency bands.

Tunable lumped components like PIN diodes, varactor diodes, and switches are commonly used to achieve frequency reconfigurability. In [4], PIN diodes were employed to change the antenna current distribution, and as a consequence, the frequency, radiation pattern, and polarization can be tuned. Varactor diodes were used in [5] to reduce the patch-antenna size and to obtain a wide frequency tuning range. In [6], a microfluidically-reconfigurable patch antenna was introduced, and the operation between two frequency bands of 28 GHz and 38 GHz can be toggled. An optically-controlled reconfigurable antenna based on photoconductive switches can also achieve the same two operating frequency bands in [7]. A new reconfigurable concept based on a multi-feed cluster was proposed in [8]. Multiple mutually coupled antenna elements of different resonances were used to achieve frequency tunability by adjusting the feeding weights of each port.

However, there is no published paper on dual-polarized frequency-reconfigurable mm-Wave antenna for a smart phone. In this paper, we propose a square patch antenna of dual polarization and a large frequency tuning range covering the whole mm-Wave frequency band from 23 GHz to 45 GHz. The effect of the quality factor (Q) of the tuning components on the antenna efficiency is studied. Antenna structure with ideal lumped components are simulated in CST to demonstrate the expected performances.

II. FREQUENCY-RECONFIGURABLE ANTENNA AT MM-WAVE FREQUENCY BANDS

A. Antenna Structure

A dual-polarized square patch antenna loaded with varactor diodes is proposed to achieve the frequency tunability at mm-
TABLE I
DIMENSIONAL PARAMETERS OF THE ANTENNA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( L_g )</th>
<th>( L_p )</th>
<th>( L_1 )</th>
<th>( L_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (mm)</td>
<td>3.7</td>
<td>1.7</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( L_3 )</th>
<th>( H )</th>
<th>( D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (mm)</td>
<td>0.6</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Wave frequency bands. As shown in Fig. 1, a square patch is located in the center and surrounded by four metallic L-shaped grounded walls. Four ideal varactor diodes are placed on the corners of the patch. The substrate is Megtron7 with relative permittivity \( \epsilon_r = 3.0 \) and loss tangent \( \tan \delta = 0.0027 \). In addition to practical feeding network, two 50-Ω lumped ports are used for simulation in CST. Specific dimensions are given in Table I.

B. Frequency Tunability

Generally, a loaded patch antenna can be illustrated with a transmission-line model as shown in Fig. 2a. The resonance occurs when \( Im(Y_{in}) = 0 \):

\[
Y_{in} = Y_L + jY_{var} = Y_L \sin(\beta L) + Y_{Load} \cos(\beta L)
\]

where the \( Y_{Load} \) is the admittance of the radiator. For the loaded patch antenna, the admittance can be written as:

\[
Y_{Load} = Y_S + Y_{var}
\]

where \( Y_S \) and \( Y_{var} \) are the admittance of the equivalent slot radiator and tuning component, respectively. Hence, the resonant frequency of the patch antenna can be tuned by adjusting the \( Y_{var} \).

The simulated S-parameters of different capacitance values are given in Fig. 3. Because of the symmetrical structure, the results of \( S_{12} \) and \( S_{22} \) are omitted. It can be seen that the frequency tunability is realized by tuning the capacitance values. When \( C \) is 0.005 pF, the proposed patch antenna covers the frequency bands n259 and n260 from 37.5 GHz to 43.5 GHz with 10-dB return loss. When \( C \) increases from 0.03 pF to 0.05 pF, it can cover the frequency bands n257, n258, and n261 from 24 GHz to 29.5 GHz. The needed capacitance tuning range is ten to one (maximum/minimum). In addition, isolation level between the two polarizations is higher than 15 dB from 24 GHz to 42 GHz, and the worst isolation level is still higher than 13 dB at the highest frequency point. We can see that the required smallest capacitance is 5 fF that is not available in the current market. The MAVR-011020-1411 from MACOM has a capacitance value as low as 0.025 pF, making it possible for further experimental work, and a series capacitor can be utilized to further decrease the total capacitance.

C. Antenna Efficiency

Varactor diodes can be employed to provide different capacitance values. However, additional parasitic effects are inevitable such as ohmic loss from the equivalent series resistance (ESR). Here, we use a simple equivalent circuit as shown in Fig. 2b in the proposed patch antenna for simulation. In addition, the packaging of varactors has a great influence on the antenna performance due to the large electrical size in
mm-Wave frequency band. Hence, the quality factor ($Q$) is used to estimate possible ESR and simplify the analysis. The quality factor $Q$ of the employed equivalent circuit as shown in Fig. 2(b) can be presented as:

$$Q = \frac{1}{2\pi f C R}$$  \hspace{1cm} (3)

In order to figure out the influences of $Q$, two different values are studied. The selected frequency $f$ is 40 GHz, and the ESR ($R$) is changed according to the values of $C$ and $Q$ as:

$$R = \frac{1}{2\pi f C Q}$$  \hspace{1cm} (4)

The resulting ESRs are given in Table II.

Fig. 4 shows the results of the antenna efficiency. The results are given here only for one port because the results for the other port are the same. It can be seen that the total efficiency decreases as the capacitance value increases. When $Q = 100$, the total efficiency drops from −2.7 dB to −1 dB. When $Q = 10$, the total efficiency drops from −0.7 dB to −2.7 dB due to the higher ESR.

### III. Conclusion

In this paper, we propose a dual-polarized frequency-reconfigurable patch antenna working at mm-Wave frequency bands. The proposed antenna has a large operating frequency band from 23 GHz to 45 GHz by tuning the capacitance value from 0.05 pF to 0.005 pF. All the mm-Wave frequency bands for mobile communications defined by 3GPP can be covered. The isolation between two polarizations is larger than 13 dB. Besides, different $Q$ values of varactor diodes are analysed, and corresponding total efficiencies are demonstrated. The total efficiencies are larger than $−2.7$ dB and $−1$ dB with $Q = 10$ and $Q = 100$, respectively, over the desired frequency bands. Furthermore, frequency-insensitive radiation patterns are observed at both low and high bands. Cross-polarization levels are lower than $−15$ dB and $−20$ dB at low and high bands, respectively. The proposed antenna is a promising candidate for the 5G handsets aiming at mm-Wave spectrum.

### TABLE II

<table>
<thead>
<tr>
<th>$R$</th>
<th>$C$ (pF)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>7.96</td>
<td>0.005</td>
</tr>
<tr>
<td>0.01</td>
<td>3.98</td>
<td>0.01</td>
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<tr>
<td>0.02</td>
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<td>0.04</td>
</tr>
<tr>
<td>0.05</td>
<td>0.796</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### REFERENCES


