A Wideband mmWave Microstrip Patch Antenna Based on Zero-Mode and TM-Mode Resonances

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Abstract: Millimeter wave (mmWave) antennas for 5G communication require wide bandwidth, directional radiation patterns, low-profile design and multi-layer compatibility for module-level integration. In this paper, we introduce a method of loading shorting pins to a patch antenna to generate extra zero-modes. By merging the 2nd zero-mode, TM01 mode, 3rd zero-mode and TM20 mode in the frequency spectrum, a wide bandwidth varying from 23 to 34 GHz (relative bandwidth of 38.6%) and with a low-profile of 0.762 mm (0.07λ0, where λ0 is the wavelength at a middle frequency of 28.5 GHz) can be obtained. Based on this wideband patch antenna, a 4 × 2 antenna array is obtained with the ±40° scanning performance. Theoretical analysis, full-wave simulations and experimental performances are presented, validating the effectiveness of this method to achieve a wideband performance in a mmWave band. It can be applied to 5G communication systems using mmWave bands.

Keywords: millimeter wave antenna; shorting pins; UWB; zero mode; CPW structure

1. Introduction

The millimeter wave (mmWave) frequency band is one of the crucial bands for 5G (fifth-generation mobile network) communication, as it exploits abundant frequency resources, increases data bandwidth and possesses ultra-low latency. Antennas operating in the mmWave band require wide bandwidth and directional radiation patterns to cover as much as the spectrum bands utilized in different countries, and to mitigate the high propagation loss, respectively. Among so many antenna forms, several forms such as the Vivaldi antenna [1,2] and the magneto-electric dipole [3] have wideband performance. However, a microstrip patch antenna is widely used because of its low-profile, small size and the compatibility for module-level integration with multi-layer configurations. Previously, many researchers have presented different methods to expand microstrip antenna bandwidth.

In [4], a parasitic-patch-based inset-fed patch antenna with the size of 0.43λ0 × 0.32λ0 × 0.12λ0 was presented for fifth-generation applications in different countries. By adding the parasitic element with the same size as the radiation patch, the impedance bandwidth was significantly improved to be 24.4% in the 25 to 31 GHz frequency band and achieved the peak gain of 8 dBi. A stacked microstrip patch antenna with two parasitic patches, which is suitable for use in arrays and can be integrated with circuits, was proposed in [5]. The overall bandwidth of the proposed antenna achieved 35% (4.9–7.05 GHz) with the average gain of 6 dBi. In [6], a new parasitic resonator-based diamond-shaped microstrip patch antenna for ultra-wideband microwave imaging applications, with the size of 0.65λ0 × 0.54λ0 × 0.03λ0, was proposed. The proposed antenna achieved an overall bandwidth of 7.6 GHz (2.7–10.3 GHz) with more than a 4 dBi realized gain. However,
adding parasitic patches may bring large sizes and complicated structures, which is the disadvantage against mmWave bands.

Cutting slots [7–9] and using tightly coupled arrays [10] are also the common methods to improve the bandwidth of patch antennas. As shown in [11], a triangular slot-loaded planar rectangular antenna was presented for wideband 5G communication systems. The overall dimensions of the antenna element were 0.85\(\lambda_0\) × 0.63\(\lambda_0\) × 0.06\(\lambda_0\). By cutting the slots, the bandwidth was improved by 56.5% (24.5–43.8 GHz) with a gain between 3.2 and 5.7 dBi. In [12], a broadband mmWave antenna system for upcoming fifth-generation networks was presented. With the EBG reflector, the proposed antenna provided a wideband impedance bandwidth of about 75.9% (22.5–50 GHz) with an average gain of 4 dBi. Cutting slots on the patch and ground can effectively improve the bandwidth of patch antennas, but it may bring a low fabrication tolerance produced by those cutting and coupling slots.

In contrast, loading shorting pins is an appropriate approach to expand the bandwidth of patch antennas, since it not only can achieve wide bandwidth by exciting multiple TM modes [13–15] and inducing extra zero modes [16], but also is compatible with model-level mmWave antennas in which via holes are used quite regularly for multi-layer configurations. Loading shorting pins to patch antennas have been addressed in low frequency bands below 10 GHz [17]. In mmWave bands, [18] proposed an antenna with one shorting pin for inducing the TM\(_{01}\) mode and the 2nd zero mode to cover 23.5–28 GHz. Besides improving the antenna bandwidth, loading shorting pins can also improve the antenna gain [19]. In [20], a gain-enhanced patch antenna with loading shorting pins was proposed. After loading the shorting pins, the TM\(_{01}\) mode was raised, which enlarged the overall area of the antenna to achieve about 2.9 dB increments of antenna gain.

In this paper, we theoretically analyze patch antennas by loading different numbers of shorting pins, numerically calculating the input impedance and obtaining a resonance map with a uniform distribution of the 2nd zero mode, TM\(_{01}\) mode, 3rd zero mode and TM\(_{20}\) mode. Consequently, by combining these modes, a patch antenna with the size of 0.41\(\lambda_0\) × 0.31\(\lambda_0\) × 0.07\(\lambda_0\) is modeled and a bandwidth as wide as 23–34 GHz can be achieved. A 4 × 2 antenna array is also designed to resist the high propagation loss of the mmWave band. Full-wave simulations and measurements are demonstrated to verify this method can be used to obtain a wideband performance.

2. Theoretical Analysis

A regular microstrip antenna with loading shorting pins is shown in Figure 1a. The probe-fed antenna consists of a rectangular patch on the top layer, a dielectric substrate layer (Rogers RO4350, \(\varepsilon_r = 3.48, \tan\delta = 0.0037\)) with the RF ground on the bottom layer and shorting pins made as via holes going through the substrate. Considering this antenna model as the standard cavity model, the wave equation in the cavity can be written as [21]:

\[
E_z(x, y) = j\omega\mu_0 \int \int G(xy, x'y')j_z(x', y')dx'dy'
\tag{1}
\]

where \(\mu_0\), and \(j_z\) are the permeability of free space and the \(z\)-directed current density, respectively. Specifically, the Green function \(G(xy, x', y')\) is

\[
G(xy, x', y') = \sum_{n, m} \frac{\psi_{nm}(xy) \psi_{nm}(x'y')}{k_{nm}^2 - k^2}
\tag{2}
\]

where \(k\) is the wave number in the substrate, and \(k_{nm}\) is the wave number of the mode \((n, m = 0, 1, 2, 3, \ldots)\). The eigenfunction \(\psi_{nm}\) is expressed as

\[
\psi_{nm}(x, y) = \frac{1}{\sqrt{W_pL_p}} \frac{\varepsilon_i}{\varepsilon_i} \frac{\cos\left(\frac{n\pi x}{W_p}\right)}{W_p} \frac{\cos\left(\frac{m\pi y}{L_p}\right)}{L_p}
\tag{3}
\]

\[
\varepsilon_i = \begin{cases} 
1 & i = 0 \\
2 & i \neq 0
\end{cases}
\tag{4}
\]
\[ k_{nm}^2 = \left( \frac{n\pi}{W_p} \right)^2 + \left( \frac{m\pi}{L_p} \right)^2 \]  

(5)

where \( \sigma_i \) is the Neumann number, and \( W_p \) and \( L_p \) are the length in \( x \)-direction and width in \( y \)-direction, respectively, as shown in Figure 1a.

Figure 1. (a) Three-dimensional view and (b) side view of a regular microstrip antenna employing three shorting pins with dimensions of (mm): \( W_s = 5.7, L_s = 7.5, H_s = 0.762, W_p = 3.3, L_p = 4.3, d = 0.2, D = 0.3, x_1 = 1.1, x_2 = -1.3, x_3 = 0, x_4 = 0.71, y_1 = 0, y_2 = -0.8, y_3 = -1.8, y_4 = -2. \)

As shown in Figure 1b, the feed probe located at \((x_1, y_1)\), and, together with the three shorting pins located at \((x_2, y_2), (x_3, y_3), (x_4, y_4)\), can be regarded as a four-port network, in which relative voltages and currents are \((V_1, I_1), (V_2, I_2), (V_3, I_3)\) and \((V_4, I_4)\), respectively. Employing three pins at the locations of \((x_2, y_2), (x_3, y_3), (x_4, y_4)\) induces the condition of

\[
\begin{align*}
E_x(x_2, y_2) &= 0 \\
E_x(x_3, y_3) &= 0 \\
E_x(x_4, y_4) &= 0
\end{align*}
\]

(6)

and relative voltages are

\[
\begin{align*}
V_2(x_2, y_2) &= 0 \\
V_3(x_3, y_3) &= 0 \\
V_4(x_4, y_4) &= 0
\end{align*}
\]

(7)

Therefore, for the four-port network, voltages and currents can be expressed as

\[
\begin{align*}
V_1 &= Z_{11}I_1 + Z_{12}I_2 + Z_{13}I_3 + Z_{14}I_4 \\
0 &= Z_{21}I_1 + Z_{22}I_2 + Z_{23}I_3 + Z_{24}I_4 \\
0 &= Z_{31}I_1 + Z_{32}I_2 + Z_{33}I_3 + Z_{34}I_4 \\
0 &= Z_{41}I_1 + Z_{42}I_2 + Z_{43}I_3 + Z_{44}I_4
\end{align*}
\]

(8)

The input impedance \( Z_{in} \) from the coaxial probe can be obtained as

\[
Z_{in} = \frac{V_1}{I_1} = \frac{\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix}}{\begin{bmatrix} Z_{22} & Z_{23} & Z_{24} \\ Z_{32} & Z_{33} & Z_{34} \\ Z_{42} & Z_{43} & Z_{44} \end{bmatrix}}
\]

(9)

in which \( Z_{ij} \) (\( i = 1, 2, 3, 4, j = 1, 2, 3, 4 \)) is the mutual impedance as

\[
Z_{ij} = \frac{E_z(x_i, y_i, x_j, y_j) + H_s}{I_j}
\]

(10)
In Equation (10), $H_s$ is the thickness of the antenna substrate, and $E_z(x_i, y_i, x_j, y_j)$ is defined as Equation (1). Based on these equations, we can calculate the input impedance, thereby mapping resonances of zero modes and TM modes.

3. Calculations and Simulations

Based on Equations (1) and (9), we numerically calculated the input impedance of the antenna shown in Figure 1 by using MATLAB. The proposed antenna design was started by, firstly, designing a typical patch antenna without loading shorting pins. As shown in Figure 2a,b, when the antenna was loaded without a shorting pin, there were only two resonant modes in the frequency range from 5 GHz to 38 GHz, which were the TM$_{01}$ mode and TM$_{20}$ mode. The TM$_{01}$ mode was located near 19 GHz and the TM$_{20}$ mode was located near 28 GHz, which were too far apart for the possibility of expanding bandwidth.
Although resonances in the map were not distributed uniformly and had large separation, they indicated the possibility for wide bandwidth through the merging of these four modes by adjusting resonances. In order to make the 2nd zero mode, TM01 mode, 3rd zero mode and TM20 mode distribute more uniformly and closely on the frequency spectrum, thereby facilitating the resonances merging and also moving the input impedance curve to achieve good impedance matching at 50 ohms, the second and third shorting pins were added, as indicated in Figure 1a. As compared to Figure 2c,d, adding the second shorting pin enabled the 2nd zero mode and TM01 mode to move towards upper frequencies, namely moving resonances from around 17.8 GHz and 24 GHz to 21.3 GHz and 25.6 GHz, respectively, but little affected the 3rd zero mode and TM20 mode, which meant keeping them at 31 GHz and 35.5 GHz, respectively. Following this trend, the third shorting pin was introduced to further improve the spectrum map. It made the resonances distribute more uniformly and tightly, and enabled the 2nd zero mode located at around 25 GHz, TM01 mode at around 27.5 GHz, 3rd zero mode at around 31.5 GHz and TM20 mode at around 35 GHz to be merged as a wide bandwidth.

To verify the theoretical analysis, the same mmWave patch antenna with the final size of 4.3 mm (0.41λ0) × 3.3 mm (0.31λ0) × 0.762 mm (0.07λ0), as shown in Figure 1, was modeled and simulated with ANSYS HFSS. As shown in Figure 2e,f, simulated impedance curves demonstrated a similar map as in the theoretical case, and simulated curves of these four modes fluctuated more smoothly. Thanks to the spectrum map with a uniform and tight resonance distribution, a bandwidth as wide as 24–36.6 GHz (relative bandwidth of 41.6%) was obtained, as shown in Figure 3a. The average gain of the antenna unit in the operating bandwidth achieved about 6 dBi, as shown in Figure 3b, and the maximum gain of the antenna unit achieved about 7 dBi, which may be affected by the directional pattern.

Figure 2. Resonance maps including 1st zero mode, 2nd zero mode, TM01 mode, 3rd zero mode and TM20 mode. (a,b) Numerically calculated real and imaginary impedance from theoretical analysis with and without shorting pin. (c,d) Numerically calculated real and imaginary impedance from theoretical analysis with different number of shorting pins. (e,f) Simulated real and imaginary impedance from ANSYS HFSS with different number of shorting pins.
In order to display the influence of loading shorting pins on the current more clearly and to further verify the results of the antenna with a wide bandwidth, we also obtained the surface current distribution for antennas with and without shorting pins at various frequencies. As shown in Figure 4a,b, the surface currents of the TM01 mode and TM20 mode were mainly concentrated at the edge of the patch, whereas the surface currents of the 2nd zero mode and 3rd zero mode, shown in Figure 4c,e, were mainly concentrated at the shorting pins, which were obviously different from that of the TM01 mode and TM20 mode. The different surface current distribution clearly demonstrated the existence of the extra zero-mode resonance induced by the loading of shorting pins. For the TM01 mode, by comparing Figure 4a,d, it is shown that the surface current at the left edge of the antenna with shorting pins was disturbed due to the left two shorting pins, which resulted in the difference with that of the antenna without shorting pins. For the TM20 mode, by comparing Figure 4b,f, it is shown that the surface current at the upper edge of the antenna with shorting pins was disturbed slightly due to the upper shorting pin. Therefore, the surface current distribution was similar to that of the antenna without shorting pins.

**Figure 3.** (a) The simulated S11 parameter from ANSYS HFSS. (b) The simulated gain from ANSYS HFSS.

**Figure 4. Cont.**
Figure 4. The surface current distributions of (a,b) antenna without shorting pin at TM$_{01}$ and TM$_{20}$ mode and (c–f) antenna with shorting pins at 2nd zero mode, TM$_{01}$ mode, 3rd zero mode and TM$_{20}$ mode.

4. Experimental Demonstration

In order to facilitate the connecting and testing with the antenna model shown in Figure 1, we particularly designed a CPW (Co-Planar Waveguide) structure on the bottom of the antenna to connect with the coaxial probe, which is fed by the SMPM connector, as shown in Figure 5a,b. The size and positions of the patch and shorting pins were the same as in Figure 1, but the dimension in the x-direction became larger because of the addition of the CPW structure and the RF connector pad. As shown in Figure 5c, the simulated and measured S$_{11}$ parameters of the mmWave antenna demonstrated that it had the wide bandwidth from 23 GHz to 34 GHz, validating this method using shorting pins as an effective one to expand bandwidth. The measured S$_{11}$ curve had more ripples than the simulated one, potentially caused by the accuracy of the fabrication, soldering and RF connectors and cables, which are sensitive to the 5G mmWave band.
bandwidth from 23 GHz to 34 GHz, validating this method using shorting pins as an effective one to expand bandwidth. The measured $S_{11}$ curve had more ripples than the simulated one, potentially caused by the accuracy of the fabrication, soldering and RF connectors and cables, which are sensitive to the 5G mmWave band.

Figure 5. (a,b) Top and bottom view of simulation and measurement models and (c) the comparison of simulated and measured $S_{11}$ parameters. Relative parameter values are (mm): $W_s = 5.7$, $L_s = 13.7$, $W_p = 3.3$, $L_p = 4.3$, $W_1 = 0.8$, $W_2 = 0.6$, $D = 0.5$, $d = 0.2$, $L_1 = 6.02$, $D_{CPW} = 2.59$.

5. Scanning Performance

In order to resist the high loss of the mmWave band, the array which can improve the gain of the antenna is required. However, as the gain increases, the beam width becomes narrower; therefore, the scanning performance of the antenna array is also important. In order to investigate the scanning properties of radiation patterns, a $4 \times 2$ antenna array was designed, as shown in Figure 6a,b. The array size is $22.5 \text{ mm} \times 11.4 \text{ mm} \times 0.762 \text{ mm}$, with a $5 \text{ mm}$ distance among the adjacent elements in the $y$-axis direction and $5.7 \text{ mm}$ in the $x$-axis direction. As shown in Figure 6c–f, typical frequencies of 26 GHz, 28 GHz, 30 GHz and 32 GHz were selected for studying radiation patterns. Full-wave simulations demonstrated that the array could scan within $\pm 45^\circ$ at 26 GHz, 28 GHz and 30 GHz, and $\pm 40^\circ$ at 32 GHz, respectively, with the gain fluctuation less than 3 dB in the range of 9.5–12.5 dBi, indicating good scanning properties.
and ±40° at 32 GHz, respectively, with the gain fluctuation less than 3 dB in the range of 9.5–12.5 dBi, indicating good scanning properties.

Figure 6. Antenna array and simulated performances of beam scanning. (a,b) Side view and 3D view of antenna array. (c–f) Beam scanning performances of 26 GHz, 28 GHz, 30 GHz and 32 GHz.

6. Conclusions

In this paper, a method of inducing multiple zero modes and TM modes to design mmWave antennas with wide bandwidth was proposed. Theoretical analysis with numerical calculations, full-wave simulations and measurements demonstrated that the proposed antenna, with a size of $0.41\lambda_0 \times 0.31\lambda_0 \times 0.07\lambda_0$, had a wide relative bandwidth of 38.6%, from 23 GHz to 34 GHz. It is concluded that employing a certain number of shoring pins to a patch antenna is capable of generating multiple resonated modes that are distributed uniformly and tightly in the mmWave spectrum map, and by combining these zero and
TM modes, the antenna can obtain a wide bandwidth. Compared with the methods of adding parasitic patches and cutting slots, loading shorting pins can not only improve the bandwidth of patch antennas, but can also keep the small size and simple structure. Therefore, it is suitable for mmWave application scenarios that require antennas with wide bandwidth, directional radiations and low-profiles.

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