Dual-Port Traveling-Wave Frequency-Scanned Patch Array Antenna for E-band Vehicle Sensing and Imaging Applications

Wan Jiang1a), Yong Mao Huang1, Christian Waldschmidt2 and Biao Zhang3

Abstract An E-band dual-port frequency-scanned traveling-wave array antenna enabled by series-fed microstrip patches was demonstrated in this study. By varying the distance between adjacent radiated elements, the main beam can be adjusted to any desired direction angle. Subsequently, by integrating this mechanism with the traveling-wave array antenna, a frequency-scanned antenna with simple structure is developed, which presents an excellent alternative for E-band sensing and imaging applications. The proposed antenna was constituted by 16 identical series-fed rectangular patches and two input ports with the impedance transition structures between rectangular waveguide and microstrip transmission line. With the two different feeding ports, main beam of the fabricated antenna’s radiation pattern can scan from 14° to 22° or -14° to -22° over 75 GHz to 79 GHz.

key words: Frequency-scanned, array antenna, dual-port
Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

In the past few years, microstrip patch array antennas have drawn significant attention among many researches owing to the rapid development of wireless and mobile communication [1-14]. They have many applications in wireless communication, radar, sensing and imaging systems due to their light weight, low profile and price, flexible to design and fabricate, and high robustness. More impressively, in array designs the microstrip feed network can be placed on the same substrate as the microstrip patches which has wide applications in millimeter-wave range. Series-fed microstrip patch array antennas are one of the most popular candidates in the design among the field mentioned above. Previous work on them includes, but is not limited to [15-18]. Compared with corporate-fed array antennas, series-fed array antennas utilize shorter line length which leads to an antenna with lower attenuation loss, less space on the substrate and spurious radiation from feed lines [19]. Because of high operating frequency, E-band array antennas with high gain need precise and complicated machining process which leads to a high production cost. Available antennas [20-22] usually have bulky size and weight, resulting in high shipping expenses and heavy manpower expenditure on equipment installation and adjustment.

Fig. 1. Microstrip-to-RWG transition. (a) The top side of substrate. (b) The bottom side of substrate. (c) The 3-D view.
the radiation angle and the distance of adjacent radiated elements is demonstrated. The proposed antenna has the advantages of high reliability, simple structure, and good economic benefits which is promising for the E-band wireless communication, radar, sensing and imaging applications. With different feeding ports, the main beam of the antenna’s radiation pattern can scan from 14° to 22° or −14° to −22° from 75 GHz to 79 GHz. Combining the proposed antenna design mechanism with an appropriate switch or attenuator, the main beam of the radiation pattern can scan from backward direction to forward direction continuously which has wide applications in E-band array antenna design in vehicle sensing and imaging.

![Fig. 2. Simulated S-parameter of the proposed transition between WR12 waveguide and microstrip line.](image)

| Symbol | Value (mm) |
|--------|------------|
| W      | 12.10      |
| L      | 6.33       |
| a      | 3.10       |
| b      | 1.55       |
| w1     | 0.30       |

### 2. Impedance transition design

Due to the E-band measurement system is typically configured with standard waveguide ports, the feeding method of the system is no longer using the conventional microstrip feeding. A Rohde&Schwarz’s vector network analyzer ZVA-50 and two frequency extenders were combined to extend the measurement frequency range to 90 GHz during the measurement. The output port of the frequency extender is standard WR12 waveguide, so it is essential to design the impedance transition structure between waveguide and microstrip line before carrying out the design of the proposed antenna.

Quite a few of excellent investigation have been carried out on the design of transitions between waveguide and microstrip line with different structures [23-26]. As shown in Fig. 1(c) [26], the transition utilized in this study was constituted of three parts: a WR12 waveguide (feeding perpendicular from the bottom side of the substrate), a substrate and an upper cap with rectangular flute. The target center frequency of the antenna is 77 GHz with band width of 4 GHz. Therefore, the parameters of the transition structure are set as follows: the operating frequency range is 75-79 GHz, \(|S_{11}|\) is less than -15 dB, and the insertion loss is less than 0.5 dB. The transition was performed in the Rogers RT/Duroid 3003 substrate with a thickness of 0.254 mm and a dielectric constant of 3.

The impedance transition applies electromagnetic energy coupling to convert the energy propagating from the waveguide to the planar microstrip line. The structure of the transition is simple and with strong tightness which obviates the non-ignorable parasitic parameter brought by complicated additional structures in E-band.

As the consequence of that, such transition is very suitable for application in the antenna design in the aimed frequency range. Figure 1(a) and (b) depict the top side and bottom side of the substrate, respectively. The gray parts represent metal, and the white parts represent the substrate. The size of the white area on the bottom side of the substrate is consistent with the size of WR12, that is, \(a=3.1\,\text{mm}\), \(b=1.55\,\text{mm}\), and the diameter of vias is 0.3 mm (the specific location is not marked in the figure). The rectangular patch on the top side of the substrate at the center couples the energy fed by the waveguide, and then propagate the coupled energy to the microstrip line, realizing the transition between the waveguide and the microstrip line. For the upper cap above the substrate, the depth of the flute is generally \(\lambda_0/4\), where \(\lambda_0\) is the wavelength in free space at center frequency. The end of the flute forms a reflecting surface. The energy propagated from the waveguide reaches the rectangular patch and is coupled to the microstrip line. Meanwhile, the rest of the energy reaches the reflecting surface and is reflected to the rectangular patch then coupled again. The depth of the flute ensures that the energy of the two couplings are in phase. The detailed parameters of the transition are shown in Table 1, and the depth of the flute is 0.34 mm.

The simulated results of the transition are shown in Fig. 2. It can be seen that in the frequency range of 75-79 GHz, \(|S_{11}|\) of the transition is less than -15 dB, and the insertion loss is less than 0.5 dB, which meets the requirements of the transition structure.

### 3. Antenna design

Subsequently, the dual-port traveling-wave frequency-scanned rectangular patch array antenna is investigated systematically. The radiation performance of a rectangular patch antenna is directly related to its detailed dimensions. The wider the patch width, the lower the input impedance, and the wider the bandwidth, and the higher the radiation efficiency. However, the radiation pattern of a rectangular patch with large width will produce a strong side lobe, which will affect the radiation pattern of the antenna. In addition, patches with large width may introduce high-order modes, and the above factors will affect the performance of rectangular
patch antennas. In the proposed antenna array antenna design, the width of the patch is 1.38 mm while the length is 0.986 mm.

Fig. 3. The structure of proposed E-band dual-port frequency-scanned traveling-wave array antenna enabled by series-fed microstrip patches.

The rectangular patch antenna unit can be equivalent to two radiation slots. When the array antenna unit is excited with equal amplitude and phase, the main lobe of the radiation pattern is vertical upward. As there is a phase difference between the array antenna’s elements, the main lobe direction of the antenna radiation pattern is no longer upright, that is, the main beam direction of the array antenna varies with the phase or distance between each array antenna element.

Thereafter, as mentioned above, the main beam direction of the array antenna varies with the phase or distance between adjacent radiated elements. To obtain the diversity of the radiation pattern, the distance between adjacent radiated elements is chosen as 1.18 mm, a bit smaller than half wavelength in the substrate.

With the change of the distance between two adjacent elements, the direction of the main beam tilts to an aimed angle. As shown in Fig. 3, the array antenna contains 16 rectangular patch elements. The antenna substrate coincides with the XOY plane of the coordinate system, and the array antenna is distributed along the Y-axis. It can be seen from the Fig 3, the two ports are located at both ends of the array antenna on the bottom side of the substrate. When one port is selected as the input port, the other port is open. The circular holes in the substrate and the upper cap in the transition structure are corresponding to the size of the flange plate of the waveguide interface, and are utilized to fix the waveguide structure at the bottom side of the substrate. The simulated S-parameter with energy propagated from port 1 is shown in Fig 4. Due to the similarity between fed by port 1 and port 2, only one simulated return loss is depicted here. The centre frequency of the proposed array antenna is 77 GHz with bandwidth of 4 GHz, and $|S_{11}|$ is less than -15 dB in the entire frequency range which shows the good performance of the proposed array antenna.

Figure 5(a) and (b) show the simulated radiation pattern of the proposed array antenna in the frequency range of 75–79 GHz. It can be seen that as the energy was fed from port 1, the main lobe angle of the antenna radiation pattern is near $-15^\circ$ at center frequency, i.e. 77 GHz; whereas as the energy was fed from port 2, the main lobe angle of the antenna radiation pattern is near $+15^\circ$ at center frequency. As the analysis mentioned above, the main lobe angle can be tilted by adjusting the distance between the array antenna’s elements. When the two ports are fed constantanous with equal amplitude and phase, the main beam of the radiation pattern is at $0^\circ$. Once the two ports of the antenna are connected with a suitable switch or attenuator, the diversification of the radiation pattern can be realized. In summary, the main beam can be switched between $-15^\circ$ and $+15^\circ$ or continuous sweep angle from $-15^\circ$ to $+15^\circ$ with suitable switches or attenuators. In the specific design, the main lobe angle can be adjusted to a suitable range according
to different application scenarios and combined with suitable active switches, fast and accurate beam-forming can be performed according to the different demand of the E-band radar system. Moreover, the main beam sweeps with the change of frequency which shows the frequency-scanned characteristic which is shown in Fig. 5. The array antenna contains 16 elements, even if one port is in an open circuit while the other port is the input port, the reflected energy can be ignored due to the large element number. The radiation characteristics of the antenna can be equivalent to a traveling-wave antenna, so the main beam of the radiation pattern will follow the change of the frequency which exhibits the characteristics of a frequency-scanned antenna. As shown in Fig. 5(a), when energy is fed from port 1, the main beam swept from -12° to -20° within the frequency range from 75 GHz to 79 GHz. On the other hand, when energy is fed from port 2, the main beam swept from 12° to 20° within the frequency range from 75 GHz to 79 GHz which is depicted in Fig. 5(b).

4. Antenna fabrication and measurements

Afterwards, the proposed dual-port traveling-wave frequency-scanned patch array antenna shown in Fig. 6(a) and (b) was fabricated and measured for verification using Rogers RT/Duroid 3003 substrate with thickness of 0.254 mm and permittivity of 3. The total length of the antenna is 88 mm while the width is 33 mm. The detailed fabricated transition structure between the waveguide and the microstrip and the upper cap with rectangular flute are shown in Fig. 7. There are top view, bottom view and upper cap from left to right. The waveguide is fed from the bottom of the substrate, and the energy is coupled to the microstrip line through the transition structure and then transmitted to the rectangular patch array antenna. As mentioned above, the S-parameter was measured with a Rohde&Schwarz’s vector network analyzer ZVA-50. The upper limit of frequency of the vector network analyzer is 50 GHz. Two additional frequency extenders were added to the measurement system. Therefore, as shown in Fig. 8, a Thru-Reflect-Line (TRL) calibration kit is designed and fabricated to enable the calibration surface of the vector network analyzer to the input port of the first rectangular patch. The three calibration structures in the figure from left to right are: Thru, Line and Reflect. In the Line standard, the length of the microstrip line is set as a quarter wavelength in the substrate at center frequency. In order to ensure that the array antenna and calibration kit remain stable during the measurement, the fabricated array antenna and the calibration kit are fixed with aluminum plates with a thickness of 1 cm. The aluminum plates were assembled with the substrate by plastic screws. Moreover, the aluminum plate provides a stable path for the waveguide feed port on the bottom side of the substrate. The aluminum plate is designed specifically according to the proposed antenna and the TRL calibration kit, and serves as a support for the substrate, so that the antenna remains stable during the entire measurement process.

![Fabricated E-band dual-port frequency-scanned traveling-wave array antenna enabled by series-fed microstrip patches. (a) Top view; (b) Bottom view.](image)

![The detailed fabricated transition structure between the waveguide and the microstrip and the upper cap with rectangular flute.](image)

![The comparison between the simulated and measured S-parameters of the proposed E-band dual-port traveling-wave frequency-scanned patch array antenna](image)
Figure 9 shows the comparison between the simulated and measured S-parameters of the proposed $E$-band dual–port traveling–wave frequency–scanned patch array antenna. Generally speaking, the measured S-parameter is in good agreement with the simulated results within the frequency range from 75 GHz to 79 GHz. The measured and simulated $|S_{11}|$ trend of the antenna is basically the same and both are less than -10 dB in the operating frequency range, which meets the performance requirements of the $E$-band array antenna. The difference between the simulation and measurement is mainly caused by the fabrication tolerance.

Figure 10 depicts the measured radiation pattern in the frequency range from 75 GHz to 79 GHz with energy input from port 1 and port 2, respectively. It can be obtained that the measured frequency-sweeping performance of the antenna are consistent with its simulations. The main beam of the fabricated array antenna’s radiation pattern scans from $-14^\circ$ to $-22^\circ$ or $14^\circ$ to $22^\circ$ from 75 GHz to 79 GHz, as depicted in the measured results. The proposed $E$-band dual–port traveling–wave frequency–scanned patch array antenna has the advantages of simple structure and high stability. For practical $E$-band applications including vehicle sensing and imaging, the proposed antenna provides a low-cost, high-stability method for realizing the diversity of the radiation pattern. Furthermore, based on the proposed design process, the sidelobe level (SLL) of the array antenna will be reduced if Taylor distribution was applied.

Several excellent published automotive antennas with various mechanisms are presented in Table 2. All of them have done superior researches among automotive radar antennas. Although series-fed rectangular patch array antenna has been widely studied, this table shows the difficulty in achieving such kind of array antenna in automotive array antenna in aimed frequency range with simple structure. Overall, the advantages of the proposed design process of the dual-port series-fed frequency-scanned traveling-wave patch array antenna in $E$-band is mainly in the simple structure, low cost, high design reliability and diversity of radiation pattern which has excellent economic benefits and wide applications in $E$-band array antenna design in vehicle sensing and imaging.

### 5. Conclusion

An $E$-band dual–port traveling–wave frequency–scanned patch array antenna was demonstrated in this work. With the variation of the distance between adjacent radiated elements, the main beam can be adjusted to any aimed direction angle. The proposed antenna combined this mechanism with traveling-wave array antennas to realize frequency-scanned antenna design with simple structure. The main beam of the fabricated array antenna’s radiation pattern scans from $-14^\circ$ to $-22^\circ$ or $14^\circ$ to $22^\circ$ from 75 GHz to 79 GHz with different feed port. Combining the proposed antenna design mechanism with an appropriate switch or attenuator, the diversity of radiation pattern can be realized which has significant potential applications in $E$-band sensing and imaging systems.

### Table 2 Comparison of performance to existing results in literature

| Ref. | Frequency | Features | Gain | Radiation Pattern Diversity |
|------|-----------|----------|------|-----------------------------|
| [27] | 77/79 GHz | 12-layer of LTCC | 7.5 dBi | No |
| [28] | 77/79 GHz | Multi-layer grid structure | 10.5 dBi | No |
| [29] | 77 GHz | Horn array | 15 dBi | No |
| [30] | 77 GHz | Multi stub radiator | 9.5 dBi | No |
| Proposed | 75-79 GHz | Single-layer array antenna | 14 dBi | Yes |
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