A novel 94 GHz planar integrated monopulse array antenna with hybrid feeding networks

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Abstract: A W-band low-sidelobe high-gain planar integrated monopulse array antenna is presented in this paper. The antenna comprises two PCB layers, one is $16 \times 41$ units series-fed patch arrays and the other is a low-loss slot feeding network based on substrate integrated waveguide (SIW) technology. A W-band waveguide magic T is used in this design in order to get sum and difference beams in horizontal azimuth. Such a two-layer integrated array antenna can be fabricated with standard multi-layer PCB process. The maximal measured gain of the proposed antenna is 26.63 dB, while the maximal null-depth is measured to be is $-32.1$ dB. Quarter-wavelength transformers are used to achieve Taylor’s amplitude distribution in order to suppress sidelobe. The measured sidelobe level in the vertical plane is within the range of $-25.7$ dB to $-26.4$ dB. The designed monopulse array antenna has great practical value in W band portable radar.

Keywords: monopulse array antenna, integrated, low-sidelobe, high-gain, magic T, substrate integrated waveguide (SIW)

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

The atmospheric radio window at W band has more advantages in portable radar than other bands for the sake of high sensitivity, small size. As a key component of the radar system, the performance of the antenna directly affects the performance of the entire radar system [1]. In the conventional methods, reflector antenna and slotted waveguide array antenna are widely used in W band radar system because of its high directivity and simple structure. However, due to features like large size and heavy weight, these antennas will not be applicable to portable radar system.

The slot array antennas based on single layer Substrate integrated waveguide (SIW) have been reported in [2] and [3]. Because of PCB process, these antennas are much lighter than the traditional reflector antenna [4, 5, 6] and slotted waveguide antenna [7, 8]. However, the feeding networks in these antennas are too complicated. This leads to large path losses and will also cause the decrease of antenna gain. As is well known that the antenna gain will affect the radar detection range and transmit power. [3] presents a single-layer $32 \times 32$ slots monopulse antenna array at 94 GHz, the maximal gain is measured to be 25.8 dB. And SIW comparator is introduced in this design. However, it brings almost 4.66 dB loss to the antenna.

A variety of patch array antennas fed by SIW slots are described in [9, 10, 11]. Low Temperature Co-fired Ceramic (LTCC) technology are often used in these
cases, like [12, 13]. Compared to LTCC technology, standard PCB process has more advantage in price and technology maturity. In [11], a two-layer High-Gain integrated antenna array is designed. In this case, the SIW feeding network is placed in the bottom layer while patch array is on the top. This is a good way to reduce the antenna size, but the parallel feeding technology brings 6.38 dB path losses. For High-Gain planar array antennas, not only the number of antenna elements, but also the performance of the feeding network will affect the antenna gain. So reducing the feeding network losses is crucial to improving the performance of the array antenna.

This paper presents a two-layer High-Gain patch antenna array using series feeding technology. Compared with parallel feeding [11], series feeding reduces the complexity of the feeding network. As a result, total path losses are greatly decreased. Meanwhile, the whole antenna size is smaller than the traditional single layer one. Another difference is that series fed weighted patches are used as the sub-array in this paper. Each sub-array is composed of 41 Taylor Distribution weighed patches. So ultra-low E-plane sidelobe level (−34.54 dB simulated while −25.7 dB measured at 94 GHz) is achieved. The proposed planar antenna array will get high gain (26.63 dB maximum) using just 16/41 patches with the size of 50/140 × 0.72 mm². Such a two-layer microstrip antenna can be fabricated with standard multi-layer PCB process. It is also worth noting that the designed antenna can radiate a narrow beamwidth and low sidelobe pattern on the vertical, a sum and difference beam on the horizontal. In order to get sum and difference beams in horizontal azimuth, a W-band waveguide magic T is used in this design instead of the traditional SIW comparator. Finally, a prototype monopulse array antenna is fabricated and measured to verify our design.

2 Antenna configuration

As described in Fig. 1(a), 16 sub-arrays are etched on Rogers 5880 substrate (εr = 2.2, tan δ = 9 × 10⁻⁴) with thickness h = 0.127 mm. Using ultra-thin substrate will help suppressing surface wave in millimeter-wave antenna surface. Space between the sub-arrays is d = 2.77 mm to ensure the same phase between each sub-arrays.

Fig. 1(b) shows the upper surface of the bottom layer with 0.508 mm-thick Rogers 5880 substrate. SIW feeding networks is employed in this layer in order to transmit the TE10 wave from the waveguide. As can be seen in Fig. 1(d), which is the partial enlargement figure of Fig. 1(b), 16 coupling slots are placed is this layer to excite 16 sub-arrays on the top layer. The initial dimension of slot length is taken by \( l_{siw} = \frac{\lambda_0}{\sqrt{2(\varepsilon_r + 1)}} \).

Fig. 1(c) is the lower surface of the bottom layer. Prepunched flange holes will make a precise connection between antenna and the WR10 waveguide with UG-387/U-Mod flange. Waveguide-to-SIW feeding method is adopted in this design.

Fig. 2 explains the design configuration of the single sub-array. Each sub-array is consisted of 41 patches in order to achieve a narrow E-plane beamwidth within 3°. In order to suppress sidelobe, quarter-wavelength transformers are used to achieve Taylor’s amplitude distribution. In this design, it requires to have a −30 dB sidelobe level in vertical azimuth. So in consideration of factors like mutual
Fig. 1. Configuration of the proposed multi-layer integrated array antenna. (a) top layer, (b) middle copper layer, (c) bottom copper layer, (d) coupling slot.

Fig. 2. Sub-array configuration. Structure parameters (in millimeters): $d = 0.4$, $p = 0.6$, $w_{siw} = 2$, $w_{slot} = 0.2$, $w_{feed} = 0.25$, $l_{spacing} = 1.265$, $w_{match} = 1.9$, $l_{patch} = 1.9$, $w_{patch} = 1.9$. 
−40 dB Taylor’s amplitude distribution should be applied in the radiating patches feeding along each sub-array. Fig. 3 shows the simulated E-plane and H-plane pattern of the sub-array. Ansoft HFSS is employed to conduct the full-wave simulation and optimization. From the simulation results, we can see the E-plane has the side lobe of level −30.8 dB and 3 dB beam width of 2° at 94 GHz. The simulated Gain of the sub-array is 22 dB which is quite close to the theory limit on array antennas’ gain.

Fig. 4–5 show the simulated far field patterns of the proposed antenna at 94 GHz, 94.5 GHz, respectively. At 94 GHz, antenna gain is 33.55. Meanwhile, it realizes an ultra-low sidelobe level (−34.54 dB in E-plane and −18.27 in H-plane) at 94 GHz. Simulated E-field at 94 GHz can be seen in Fig. 6.
3 Fabrication and experiment

Multi-layer PCB layout of the proposed integrated array antenna is shown in Fig. 7. Top layer (L1) and bottom layer (L2) are bonded together by 2.1mil-thick FR-25 bonding film (L2). By high temperature lamination, three substrate layers turn into a new integrated substrate. This new substrate has a thickness of 0.72 mm.

Fig. 8 exhibits the paragraph of the fabricated planar integrated monopulse array antenna. The proposed antenna is just $50\times140\,\text{mm}^2$ in size, while the radiation aperture size is only $42.5\times85.6\,\text{mm}^2$. In order to get sum and difference beams in horizontal azimuth, a w-band waveguide magic T is used in this design as shown in Fig. 8. In [2, 3], planar substrate integrated waveguide comparator consists of directional couplers and fixed phase shifters is used. However, this may

Fig. 5. Simulated far field pattern of the proposed antenna at 94.5 GHz.

Fig. 6. Simulated E-field of the proposed antenna at 94 GHz.
cause great path loss especially at 94 GHz. So, metallic waveguide magic T is a good choice in this design than SIW comparator. Fig. 9 shows the measured S11 of the proposed monopulse array antenna with magic T. Sum and difference ports are tested separately.

Far field test results in microwave anechoic room are given in Fig. 10–12. Given that this is a very narrow beam antenna, the scanning angle scope is set from $-30^\circ$ to $+30^\circ$. Fig. 10 shows the measured E-plane sum pattern compared to simulated data at 94 GHz and 94.5 GHz. Fig. 11 gives the measured H-plane sum pattern at 94 GHz and 94.5 GHz, respectively. At 94 GHz, for the sum beam, the measured 3 dB beam-width is 2.97° in E-plane and 4.45° in H-plane. The sidelobe level is $-25.7$ dB in E-plane and $-10.8$ dB in H-plane. While at 94.5 GHz, the 3 dB beam-width is measured to be 2.87° in E-plane and 4.3° in H-plane. Also the
measured sidelobe level turns to be $-26.4$ dB in E-plane and $-13.3$ dB in H-plane. Simulated and measured results in Fig. 10–11 show good accordance in the main beam of the radiation pattern. However, the sidelobe level in H-plane is less desirable as can be seen in Fig. 11. This is due to reflected wave from the testing scaffolding when testing H-plane. So, in the next step of our work, absorbing material is needed to be attached to any possible reflective objects.
For the difference beam, as can be seen in Fig. 12, the maximum null-depth is $-32.1$ dB at 94 GHz which is in good agreement with simulated result. While at 94.5 GHz, this value is only $-28.9$ dB. This is because the scan angle-interval limit is 0.1°, so the system may not be able to receive the real null-depth signal.

The measured gain is 25.42 dB at 94 GHz while at 94.5 GHz the gain is 26.63 dB. According to measured data of magic T, the insert loss is about 0.8 dB. Waveguide to waveguide transition and waveguide to SIW transition account for a large percentage of total loss during the assembly process. In addition, PCB etching Process errors will bring the amplitude and phase errors to the antenna patches. Also multi-layer PCB bonding process will cause unknown number of loss. In general, there is still room for the antenna gain improvement.

4 Conclusion

In this paper, a 94 GHz high-gain low-sidelobe planar integrated monopulse array antenna is presented. Multi-layer and hybrid feeding networks are used in this antenna. Series-fed patches are used as the sub-array in order to realize low sidelobe in vertical plane. Measured results show that the designed antenna can achieve a maximum of 26.63 dB. The measured sidelobe level in the vertical plane is within the range of $-25.7$ dB to $-26.4$ dB. The designed antenna has great value in the application fields of W band portable radar.