Higher mode SIW excitation technology and its array application

Lubing Sun\textsuperscript{a)}, Zuping Qian, Wenquan Cao, and Yang Cai

College of Communications Engineering, PLA University of Science and Technology, Nanjing 210007, China

\textsuperscript{a}) lubingsun1993@163.com

Abstract: An excitation technology of TE\textsubscript{40} mode for substrate integrated waveguide (SIW) and its application in designing a slot antenna array is proposed. In order to excite the TE\textsubscript{40} mode, a microstrip power divider and two coupling slots driven by microstrip lines in the longitudinal direction of SIW are designed to convert the electromagnetic field pattern from slot lines to SIW. The advantages of the TE\textsubscript{40} mode are not only reducing process complexity but also simplifying the feeding network so as to reduce the production bottlenecks at high frequency. A 16-element slot array antenna fed by the TE\textsubscript{40} mode SIW is designed based on the standing wave antenna array principle. Experimental results show that a 4\times4 antenna array fed by TE\textsubscript{40} mode achieves a maximum radiation gain of 15.2 dBi and 85\% radiation efficiency at 10.4 GHz and an impedance bandwidth ranging from 9.95 to 10.6 GHz with |S\textsubscript{11}| below −10 dB. The achieved results demonstrate the superiority of the higher mode excitation technology and it is reasonable to deduce that other higher modes can be achieved based on the proposed technology.

Keywords: coupling slot, SIW, slot array antenna, TE\textsubscript{40} mode

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

References

1 Introduction

Substrate integrated waveguide (SIW) technology becomes more and more popular due to its small size, light weight, low cost and easy-integration, etc. The planar waveguide structure owns similar performance to metal waveguide through perforating metallized via array on the substrate covered by the upper and lower metal surfaces. Based on those advantages, there are many applications of SIW in filters, power dividers, couplers and antennas and one hot topic is the slot array antenna. Some of them may even have electrical properties comparable to conventional metal waveguides [1, 2, 3, 4]. As the growing applications in using the SIW to electronic systems, SIW higher order mode components are attracting more and more research interests. Higher order mode SIW has advantages in the applications, not only reducing process complexity but also simplifying the feeding network so as to reduce the production bottlenecks at high frequency.

Recently, several higher mode excitation technologies have been proposed and researched. A single-layer SIW slot array antenna with TE\(_{20}\) mode has been proposed in [5], which designed an SIW hybrid and compact 90° phase shifter to excite TE\(_{20}\) mode. In [6], a novel wideband planar direct electromagnetic wave mode transducer has been proposed for the TE\(_{20}\) mode in the SIW. A multilayer balun was designed to generate the TE\(_{20}\) mode of SIW to realize the multimode transmission [7]. Two wideband direct TE\(_{20}\) mode excitation structures were proposed and measured, both of them can be widely applied in microwave and millimeter-wave circuits and antenna feeding networks [8]. Moreover, there are also some researches in resonant cavity higher mode. High-order resonant modes inside the cavity excited by a coaxial probe have been researched and applied in circularly polarized antenna and also show good performance [9, 10].

In this paper, a direct excitation technology of SIW TE\(_{40}\) mode has been proposed and a 4×4 slot array antenna has been designed as an application. A microstrip-slot-SIW transition structure has been applied to excite the TE\(_{40}\) mode. Different from the resonant cavity mode, it is based on the transmission line mode.
The antenna array operates at 10.4 GHz and good performance is obtained without metallized via inside SIW. The measured results show that the designed antenna has a good performance with high gain, low profile, low side lobe and low cross polarization level.

2 Antenna configuration

The geometry of the slot array antenna is shown in Fig. 1, which mainly consists of two parts: a mode transition structure and a 4×4 slot array. It is a single-layer substrate with two metal layers, on which the microstrip power divider, slots and SIW are fabricated. The novel part of this study is the mode transition structure. Mode transition structure is composed of a microstrip two-way power divider with equal magnitude but 180° phase shift at two outputs and two coupling slots in the longitudinal direction of SIW. One branch is half-wavelength longer than the other to achieve the 180° phase-reverse so as to make sure the electric vector distributions in the two coupling slots are same. Otherwise, when the electric field spreads into the SIW from the coupling slot, the middle two electric fields in SIW (as shown in Fig. 2) will have the same phase and finally leads to failure in TE40 mode excitation. The width of the coupling slots is 0.4 mm and $L_s$ is the length that the slot extends into the SIW, which should be the half-wavelength to make it resonate at center frequency. The width of SIW, $W_{siw}$, is chosen based on the TE40 mode cutoff frequency. The antenna radiating part is composed of a 4×4 slot array. The designed antenna array follows the principle of standing wave radiation. To ensure that the slot with the same phase excitation, the length of the slot $L_1$ is half-wavelength, the slots are staggered distribution with intervals ($d_2$) of half-wave-guide length. All slots have same slot offsets and widths, both of them are 0.4 mm. Other optimized values are listed in Table I. Different from the conventional

![Fig. 1. Geometry of the proposed antenna array. (a) top view. (b) bottom view.](image)

![Table I. Optimized dimensions (Unit: mm)](table)

<table>
<thead>
<tr>
<th>$W$</th>
<th>$L$</th>
<th>$W_{siw}$</th>
<th>$L_{siw}$</th>
<th>$W_0$</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$W_1$</th>
<th>$W_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>110</td>
<td>56</td>
<td>70</td>
<td>0.4</td>
<td>11.3</td>
<td>11</td>
<td>2.2</td>
<td>0.8</td>
</tr>
<tr>
<td>$W_{via}$</td>
<td>$d_1$</td>
<td>$d_2$</td>
<td>$d_3$</td>
<td>$d_4$</td>
<td>$L_s$</td>
<td>$W_s$</td>
<td>$d$</td>
<td>$p$</td>
</tr>
<tr>
<td>10.5</td>
<td>6.85</td>
<td>13.7</td>
<td>12.6</td>
<td>14.8</td>
<td>9.75</td>
<td>28</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>
design, the proposed 4×4 slot antenna array is fed by \( \text{TE}_{40} \) mode directly rather than the dominant \( \text{TE}_{10} \) mode. Thus, the feeding network can be simplified so that relaxing fabrication limit.

The theory to excite the \( \text{TE}_{40} \) mode in SIW can be seen in Fig. 2. Fig. 2(a) shows the electric vector distribution on the cross section of the coupling slots in AB plane [xz plane in Fig. 2(b)]. It is similar to the electric vector distribution in \( \text{TE}_{40} \) mode SIW. Both of the electric vector distributions are antisymmetric related to their center. According to the field theory, it is possible to excite the \( \text{TE}_{40} \) mode along the slot extended into SIW. When the electric field spreads into the SIW from the coupling slot, the horizontally polarized electric field in the coupling slot would be transformed into vertically polarized field of the SIW. The symmetric plane of the coupling slot is an electric wall, so the electric field at both sides of the coupling slot in SIW are 180° out-of-phase automatically. \( W_S \) should be chosen to make sure that two coupling slots are along the quarter line of the \( W_{\text{siw}} \), as shown in Fig. 1(b). Therefore, \( \text{TE}_{40} \) mode pattern can be excited.

Fig. 2. (a) Electric vector distribution on the cross section of coupling slots in AB plane. (b) Electric vector distribution in the mode transition structure. (c) S-parameter of the mode transition structure.
The electric vector distribution at the frequency at 10 GHz of the TE_{40} mode is exhibited in Fig. 2(b), which proves the good performance of the proposed structure. Fig. 2(c) shows the S-parameter of the mode transition structure in HFSS simulation results. The reflection coefficient S_{11} (1:1) is below −15 dB except for 10.7 to 11.5 GHz, the transmission coefficient S_{21} (2:4, 1) (‘2’ represents the port2, ‘4’ represents the TE_{40} mode, ‘1’ represents the port1, other notations can also be interpreted like this) is better than −2 dB, and the transmission coefficient for TE_{10}, TE_{20} and TE_{30} modes [S_{21} (2:1, 1), S_{21} (2:2, 1) and S_{21} (2:3, 1)] are below −25 dB, −35 dB and −20 dB at the frequency range from 8.5 to 12 GHz, which certify the transition structure generates the TE_{40} mode directly and suppresses the other modes. Relatively high insertion loss S_{21} (2:4, 1) is mainly due to the coupling slot transmission loss.

3 Result

The Rogers 5880 dielectric substrate is used with a permittivity of 2.2, a thickness of 1.016 mm, and dielectric loss tangent of 0.0009. Fig. 3 gives the photograph of the proposed slot array antenna. Microstrip power divider structure and slot array are placed on the top layer of the substrate. The coupling slots are cut on the bottom of the substrate. Fig. 4 expresses the reflection coefficient of the proposed antenna. The measured |S_{11}| is less than −10 dB from 9.95 to 10.6 GHz with a relative bandwidth of 5.8%. Fig. 5 gives the gain and radiation efficiency of the proposed antenna.
antenna. The measured gain varies from 13 to 15.2 dBi with $|S_{11}|$ less than $-10$ dB. The maximum radiation efficiency of the entire measured band is 85%. Fig. 6 shows the normalized radiation patterns of the proposed antenna array at 10.4 GHz. The H plane [yz plane in Fig. 1(a)] pattern is shown in Fig. 6(a) and E plane [xz plane in Fig. 1(a)] pattern is shown in Fig. 6(b). Reasonable agreements are achieved between the simulated and measured results. The cross-polarization is below $-25$ dB and the measured first side lobe level is below $-12$ dB, which can be accepted in view of the process error and measurement error.

4 Conclusion

In this paper, a direct excitation technique of TE$_{40}$ mode has been proposed and applied in slot array antenna. A microstrip to coupling slot transition structure has been put forward to excite the TE$_{40}$ mode and shows favorable property, which can be widely applied in antenna feeding network. In the proposed antenna, high gain of 15.2 dBi and radiation efficiency of 85% are achieved at 10.4 GHz with 5.8% relative bandwidth ($|S_{11}| \leq -10$ dB). Compared to the conventional SIW slot array antenna fed by TE$_{10}$ mode, the proposed antenna has a simplified feeding network which reduces the process complexity and is beneficial for relaxing the fabrication tolerance and limit for high frequency applications.