A SIW Antipodal Vivaldi Array Antenna Design

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A kind of compact SIW (substrate integrated waveguide) Vivaldi array antenna is proposed and analyzed. The antenna consisted of 4 Vivaldi structure radiation elements fed by an equal power divider with SIW technology. The radiation element is composed of antipodal index gradient microstrip lines on both sides of the substrate. The measured reflection coefficient of the array antenna is less than $-10\,\text{dB}$ from 8.88 GHz to 10.02 GHz. The measured gain of the array antenna is 13.3 dB on 9.5 GHz.

1. Introduction

The Vivaldi antenna has been used in many microwave engineering applications for its simple structure, low cross polarization, and highly directive patterns characteristics, especially in ultra bandwidth applications such as vehicular wireless communication, radar imaging, and through-the-wall imaging [1–3]. Many kinds of Vivaldi antennas have been investigated for wideband application [4, 5], and some new antipodal Vivaldi antennas have been designed to improve radiation pattern and directivity [6, 7].

An equal power divider is necessary for the antenna array feed network for equal amplitude design. The SIW multiway microwave power divider attracts a lot of attentions because of its advantages such as small structural dimension, high integration, and low cost [8–10]. A Vivaldi antenna array fed by a SIW printed on a thick substrate is proposed in [11]. A compact four-element printed Vivaldi array is designed and investigated in [12].

The SIW is able to be fabricated by standard low cost PCB technique using low loss and low cost material substrates [13]. There is often a higher return loss in an array antenna system than a single antenna one as the feeding network for an array antenna, such as T-junction or Y-junction waveguide, will introduce a discontinuity where reflection increases sharply. To reduce the return loss, many approaches have been proposed. Reference [14] focused on the structure of its linear tapered array antennas, compared the reflection coefficients of three different structures of the array antenna, and found a maximum $-10\,\text{dB}$ bandwidth of 0.8 GHz in X-band, though the bandwidth is not wide.

To broaden the bandwidth of the array antenna, a Vivaldi array antenna operating in X-band is designed and measured in this paper. Return loss is optimized in both antenna and feed network. Vivaldi antenna is used as the array antenna element for enlarging the bandwidth. To reduce the return loss, metal via-holes are added and adjusted in the SIW. The antenna consisted of 4 Vivaldi antenna elements fed by a SIW equal power divider. Each Vivaldi element is composed of antipodal index gradient microstrip lines on both sides of the substrate, and SIW-microstrip transition structure is designed for measurement and connection. Finally this paper achieved an antenna design operating in X-band.

2. 4-Way SIW Power Divider Design

A SIW is composed of two columns of cylinder metal via-holes in the side faces of a dielectric substrate and metal layers on the upper and lower faces. The transmission characteristics of a SIW are almost the same as those of its equivalent metal waveguide. As SIWs are often integrated with coplanar waveguides or microstrip lines, transition structures should be designed for the connection. The transition structure must have a low insertion loss, a wide working band, and a simple geometry to be fabricated. The SIW connected with the microstrip transition is shown in Figure I.
Table 1: Parameters of the 4-way SIW power divider.

<table>
<thead>
<tr>
<th>Parameters (mm)</th>
<th>a</th>
<th>p</th>
<th>D₀</th>
<th>h₁</th>
<th>h₂</th>
<th>h₃</th>
<th>Z₁</th>
<th>Z₂</th>
<th>D₁</th>
<th>D₂</th>
<th>D₃</th>
<th>D₄</th>
<th>t₁</th>
<th>t₂</th>
<th>t₃</th>
<th>t₄</th>
<th>W</th>
<th>D</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>12</td>
<td>1</td>
<td>0.6</td>
<td>4</td>
<td>17</td>
<td>17</td>
<td>1.6</td>
<td>0.2</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.3</td>
<td>4.9</td>
<td>5.5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

In Figure 1, a is the distance between the two columns of cylinder metal via-holes in the SIW, p is the distance between via-holes in the via-holes array. Since the field of the microstrip line is similar to the TE10 mode of the substrate integrated waveguide, the SIW-microstrip transition is generally a tapered microstrip line. The tapered line shown in Figure 2 is able to realize impedance transformation between the 50 Ω microstrip line and the substrate integrated waveguide.

As the tapered line is designed to realize impedance transformation, the left width of the tapered line W should equal the width of the 50 Ω microstrip line. The right width of the tapered line D should ensure that the impedance of the microstrip line equals that of the SIW.

For the microstrip line, as is shown in Figure 3, its width is W; thickness is t; when the thickness of the dielectric is h, the relative permittivity is εᵣ.

The impedance of the microstrip line will be

\[
Z₀ = \frac{60}{\sqrt{\varepsilonᵣ}} \ln \left( \frac{W}{2h} + \frac{W}{4h} \right) \text{ (Ω) } \quad W \leq h,
\]

\[
Z₀ = \frac{120\pi}{\sqrt{\varepsilonᵣ} \left[ W/h + 1.393 + 0.667 \ln (W/h + 1.444) \right]} \text{ (Ω) } \quad W \geq h,
\]

where

\[
\varepsilonᵣ = \frac{\varepsilonᵣ + 1}{2} + \frac{\varepsilonᵣ - 1}{2} \left[ \left( 2 + \frac{12h}{W} \right)^{-1/2} + 0.041 \left( 1 + \frac{W}{h} \right) \right] \quad W \leq h,
\]

\[
\varepsilonᵣ = \frac{\varepsilonᵣ + 1}{2} + \frac{\varepsilonᵣ - 1}{2} \left[ \left( 1 + \frac{h}{W} \right)^{1/2} \right] \quad W \geq h.
\]

The equivalent impedance of the SIW in its TE mode is

\[
Z_{TE10} = \frac{\eta}{\sqrt{1 - (\lambda/2\alpha)}}.
\]

Ordinary Y-shaped structure can achieve the power division, but its discontinuous geometry will result in high return loss in pass band. Figure 4 shows that a 4-way SIW equal power divider is designed. The parameters of the four-way SIW power splitter are shown in Table 1. As is shown in Figure 4, adding a metal via-hole in the 90-degree bend of the SIW can reduce the power reflection when the electric field distribution of the Y-junction is changed by surface current distribution of the metal via-hole inductance. By adjusting the diameter and position of the via-hole, the least reflection can be obtained after simulation.

For parameters in Figure 4, D₀ is the diameter of the via-holes, h₁ is the width of the connection structure, h₂ is the width of the first section of Y-junction structure, h₃ is the width of the second Y-junction structure, Z₁ is the thickness of the dielectric slab, and Z₂ is the thickness of PEC in the simulation setting. It can be seen that D₁, D₂, D₃, and D₄ are the diameters of the inductive via-hole while t₁, t₂, t₃, t₄, w₂,
Figure 4: 4-way SIW power divider.

and $w_4$ determine the position of the via-holes. One via-hole is on the perpendicular bisector of the entire structure and the other two via-holes are on the perpendicular bisectors of the two upper Y-junctions, so there are no parameters $w_1$ and $w_3$.

To be tested by coaxial cable, five SIW microstrip transitions are connected with the SIW power splitter. The parameters of the microstrip transitions mentioned above are $W$, $D$, and $H$. $W$ equals 2 and $D$ equals 3.2, which ensures the impedance transformation of the 50 Ω microstrip line and the SIW. $L$ is optimized to 4.5 for the least reflection loss.

After all the via-holes get their optimized diameter and position that are shown in Table 1, the 4-way SIW power divider is simulated. The permittivity of the substrate is 4.3, and the loss tangent is 0.0015 as used in this design. The simulated $S$-parameters of different ports are shown in Figure 5. It can be seen that the $S_{11}$ parameter is less than $-10$ dB from 8.5 GHz to 10.5 GHz. In Figure 5, the transmission coefficient of $S_{21}$, $S_{31}$, $S_{41}$, and $S_{51}$ is the same for the equal power division. As shown in Figure 5, the transmission coefficient of the power divider is $-6.3$ dB$\sim-6.6$ dB from 8.9 GHz to 10.07 GHz, so it is suitable for the 4-element antenna array design, and the insertion loss is about 0.3$\sim0.6$ dB from 8.9 GHz to 10.07 GHz.

The simulated surface current of the SIW divider on 9.5 GHz is shown in Figure 6. And the simulated electric field of the SIW divider on 9.5 GHz is shown in Figure 7.

3. Antipodal Vivaldi Antenna Array Design

The antipodal Vivaldi radiation element is composed of complementary structures on both sides of the substrate. The antenna element is shown in Figure 8. The upper part is the antenna radiator, the middle part is the connection structure, and the lower part is the microstrip transition. For the upper radiation part of the antenna shown in Figure 8(a), the radiator is bordered by part of an ellipse curve on the right and an index gradient curve on the left. The index gradient curve whose exponential rate $r$ equals 1 satisfies the following formula:

$$y = c_1 \times e^{rx} + c_2.$$ (4)

The Vivaldi antenna is directly fed by a microstrip line. Impedance of the microstrip is equal to that of each export of the equal power divider. A SIW-microstrip transition
structure is designed for measurement and connection. The transition section is a tapered microstrip line.

As is shown in Figure 8, $w_1$ is the antenna width, $L$ is the antenna length, $L_2$ is set for the length of straight part in SIW-microstrip transition, $L_1$ is the length of the connection part, and $L_3$ is the length of the radiator. $R$ is length of the truncated elliptic curve. The parameters of the Vivaldi radiation element are shown in Table 2.

Parameters on Table 2 are also optimized to get the best radiation characteristics of the antenna. The simulation model of antipodal Vivaldi antenna based on 4-way SIW power divider is shown in Figure 9. The dielectric substrate has a relative permittivity of 4.5 and a thickness of 1.6 mm. Parameters of the antenna and the SIW equal power divider equal those in Tables 1 and 2.

To get the optimized parameters of the diameter and position of a via-hole, $S_{11}$ of the 4-way SIW power divider is simulated when one of the parameters of the via-hole varies. Because of the symmetry of the SIW, 4 of the 9 via-holes need to be analyzed.

Figure 10 shows the simulated $S_{11}$ when the diameter of via-hole 1 $D_1$ varies from 0.3 to 0.6. It can be seen that the $S_{11}$ curve moves up when $D_1$ increases, but not very much. Then 0.5 is picked as the optimized value of $D_1$ based on the $S_{11}$ curves.

$S_{11}$ when $t_1$ varies from 3 to 6 is shown in Figure 11. In Figure 11, the $S_{11}$ curve firstly moves down and then moves up as $t_1$ increases. Therefore the optimized $t_1$ lies between 4 and 5. Obviously $S_{11}$ is vastly dependent on $t_1$, so repeated simulations were carried out for the least reflection, which have ultimately shown that 4.9 is the best $t_1$ value.

Figure 12 has shown the simulated $S_{11}$ curves when the diameter of via-hole 2 $D_2$ varies from 0.2 to 0.6. The $S_{11}$ is
Figure 9: Simulation model of the SIW Vivaldi antenna array.

Figure 10: $S_{11}$ when $D_1$ varies.

Figure 11: $S_{11}$ when $t_1$ varies.
also not very dependent on $D_2$. For both low reflection loss and wide bandwidth, 0.5 is picked as $D_2$.

$S_{11}$ when $t_2$ varies from 3 to 6 is shown in Figure 13. When $t_2$ increases, the $S_{11}$ curve firstly moves down and then moves up, but the two resonate frequencies of the $S_{11}$ curve moves right continuously. In consideration of both bandwidth and center frequency, $t_2 = 5$ is chosen.

Simulated $S_{11}$ is shown in Figure 14 when $w_2$ varies from 3 to 6. As $w_2$ increases, the two center frequencies are moving left. The optimized $w_2$ lies between 4 and 6. After repeated simulation, 5.5 is found to be the optimized $w_2$.

$S_{11}$ when $D_3$ varies from 0.3 to 0.6 is shown in Figure 15. The $S_{11}$ curve is much more dependent on $D_3$ than $D_1$ and $D_2$, which moves down as $D_3$ increases. 0.5 is picked as the optimized $D_3$.

$S_{11}$ when $t_3$ varies from 3 to 6 is shown in Figure 16. The $S_{11}$ curve firstly moves down and then moves up, but the two center frequencies keep moving right, as $t_3$ increases. 4 is picked as the value of $t_3$.

Figure 17 shows the $S_{11}$ curves of the SIW when the diameter of via-hole 4 varies from 0.3 to 0.6. The high frequency part of the $S_{11}$ curve moves up while the low frequency part moves down as $D_4$ increases. So 0.3 is picked as the optimized $D_4$ for wider bandwidth.

$S_{11}$ when $t_4$ varies is shown in Figure 18. The $S_{11}$ curve firstly moves down and then moves up as $t_4$ increases. The optimized $t_4$ lies between 7 and 8. Later simulations have found that 7 is the optimized $t_4$. 
$S_{11}$ when $t_3$ varies from 3 to 6 is simulated and shown in Figure 19. The bandwidth of the curves changes a little while the center frequencies change more when $w_4$ increases. So 4 is picked as the value of $w_4$ in consideration of the two center frequencies.

As is shown in Figure 20, a 4-element antipodal SIW Vivaldi antenna array is fabricated and measured. The total dimension of the antenna array is 85 mm $\times$ 7 mm with the feeding cable head. The parameters of the antenna array are $D_1 = 0.5$ mm, $t_1 = 4.9$ mm, $D_2 = 0.5$ mm, $t_2 = 5$ mm, $w_2 = 5.5$ mm, $D_3 = 0.5$ mm, $t_3 = 4$ mm, $D_4 = 0.3$ mm, and $t_4 = 4$ mm.

Figure 21 shows the simulated and measured reflection coefficient. Simulated results show that the reflection coefficient is less than $-10$ dB from 8.9 GHz to 10.07 GHz. And the measured reflection coefficient is less than $-10$ dB from 8.9 GHz to 10.07 GHz.
8.88 GHz to 10.02 GHz. The measurement shows agreement with the simulation.

The simulated surface current of the SIW Vivaldi antenna array on 9.5 GHz is shown in Figure 22. And the simulated electric field of the SIW Vivaldi antenna array on 9.5 GHz is shown in Figure 23.

The simulated and measured radiation patterns on 9.5 GHz of the SIW Vivaldi antenna array are shown in Figure 24. The array gain can reach 14 dB on 9.5 GHz in simulation, and the main lobe width is about 17.3°. The measured gain is about 13.3 dB, and the main lobe width is about 16.9°.
Figure 24: Pattern of the SIW Vivaldi antenna array on 9.5 GHz.

Figure 25: Simulated gain of the SIW Vivaldi antenna array.

Figure 25 is the simulated gain in operating band. It is shown that the gain is increased with frequency increasing.

4. Conclusion

A 4-way SIW equal power divider is designed, and the impedance characteristics and transmission characteristics satisfy the array design. The Vivaldi radiation element consisted of the antipodal structure. The operating bandwidth of the SIW Vivaldi array antenna is more than 1.1 GHz in X-band. And the gain of the array antenna is 13.3 dB on 9.5 GHz.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References


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