Compact Wideband Millimeter-Wave Substrate Integrated Waveguide Fed Interdigital Cavity Antenna Array

Yang Cai, Zuping Qian, Yingsong Zhang, and Dongfang Guan
Institute of Communications Engineering, PLA University of Science and Technology Nanjing, Jiangsu 210007, China

Abstract-**In this paper, a compact wideband millimeter-wave substrate integrated waveguide (SIW) interdigital cavity antenna based on a novel coplanar waveguide (CPW) fed power divider is presented. First, through combining the CPW-slotline transition and the slotline-SIW transition, a two-way power divider with S_{11} <-15dB from 34.6 GHz to 37.1 GHz and good balance performance is designed. Then, the substrate integrated cavities (SIC) are placed interdigitally based on the power divider, which makes the antenna array structure much compact. In the end, this antenna array is fabricated and measured. The results show that the proposed antenna yields an impedance bandwidth of 33.3-38 GHz (13.1%). The compact wideband millimeter-wave SIW interdigital cavity antenna indicates a wide application foreground as its distinguish compact-size feature especially when the cavity number is relatively big.**

I. INTRODUCTION

Millimeter-wave communication system operating at 30-300GHz have attracted increasing attention for many years. In order to meet the communication requirement, the millimeter-wave antennas should obtain the capabilities of low-cost, high gain, easy fabrication and so on.

As planar embedded waveguide, substrate integrated waveguide (SIW) has attracted much attention for its advantages of low loss, high power handling capability, wideband operation, coplanar integration, and so on. Based on the novel waveguide structure, many antenna arrays fed by the broad-wall slots of SIW have been proposed. The impedance bandwidth in [1]-[3] were typically smaller than 7%. A 4×4 SIW slot antenna array [4] achieved 10.7% impedance bandwidth for 10-dB return loss. However, the gain performance suffered a large variation of up to 11dB in the impedance bandwidth.

To overcome the drawbacks mentioned above, [5] proposed an SIW slotted narrow-wall fed cavity antenna. As the dual resonance generated from both the slot and the SIW slotted-cavity, the working bandwidth of the proposed antenna could be broadened effectively. Furthermore, a 2×2 antenna array working at 35GHz was designed. The measured results showed that the frequency range for S11<-10dB was 32.7GHz-37.4GHz and the maximum gain reached 10.8dB.

Considering the power divider for the SIW cavity antenna array, there are basically two types of feeding networks: T-type and Y-type [6]. Based on the basic types, multi-way broadband SIW power divider was designed. It is obvious that the width of the SIW slot antenna doubles at least as the feeding way number doubles. Besides, the length has to increase as well so as to realize the transition for more feeding ways. Therefore, because of the multiplication of the antenna array size, the traditional feeding ways have much limit to the increase of the antenna cells.

This paper introduces a novel method to design a compact wideband millimeter-wave SIW-fed interdigital cavity antenna array, which can make the structure more compact and maintain the capacities of broadband, high gain and easy integration as well. Firstly, a novel in-phase power divider fed by CPW is designed. Secondly, the SICs are arranged interdigitally in the middle of the two adjacent feeding SIW. In the end, this novel SIW interdigital cavity antenna array is fabricated and measured. All the structures in this letter are simulated with the full-wave CAD software Ansoft-HFSS and designed on Duroid 6010 substrate with a dielectric constant of 10.2 and a thickness of 0.635mm.

II. ANTENNA ARRAY ELEMENT DESIGN

Fig. 1 depicts the physical configuration of the proposed coplanar waveguide (CPW)-fed in-phase power divider, where D and S are the diameter and period of metallic vias, and W_{siw} stands for the SIW width that determines its cut-off frequency and the working frequency range of TE_{10} mode. W_{cpw} and W_c are the CPW width and the CPW slotline width designed for 50Ω operation, respectively. The rectangular with light color in Fig. 1 represents the no-ground area in the bottom layer. Besides, the vias painted with light color are used to suppress the undesired energy leakage. This power divider consists of a CPW-slotline transition and a slotline-SIW transition.

By taking the discontinuity effect and mode conversion effect between even and odd CPW modes into account, [7] created a new input-impedance-based circuit model for CPW-to-slotline transition. The extended CPW signal strip into the slotline is viewed as a probe for exciting the slotline. By this reasonable equivalent, a specific impedance formula was given to characterize the T-junction. Based on the impedance formula, the slotline width W_s is calculated to realize the impedance matchment between CPW and the slotline.

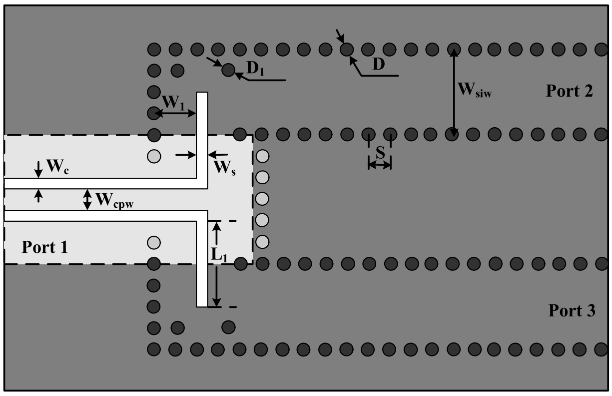


Fig 1. Geometry of the CPW fed power divider

In the second transition part, the electric field of the slotline is horizontally-polarized, which is perpendicular to that in the SIW. Because of the overlapped metallic covers on the top and bottom of the SIW, the horizontally-polarized electric field can be easily converted to the vertically-polarized field of the HMSIW [8]. Four via posts with the diameter of D_1 are used to optimize the resonance of the transition. By combining the two transition parts mentioned above, a novel CPW-fed power divider is produced. TABLE. I lists the optimized parameters of the structure. Fig. 2 shows the simulated S_{11} result of the power divider. Within the frequency range of 34.6-37.1 GHz, the return loss is less than -15 dB. Fig. 3 and Fig. 4 show that the maximum phase and amplitude imbalances within the working frequency range are less than 1.1 and 0.17 dB, respectively. These results indicate that the proposed power divider can operate in a wide band with good balance performances for both the amplitude and the phase.

Besides, the SIC size [9] comes given by a (length) and b (width) to realize S_{11} <-10dB from 33.5 GHz to 36.9 GHz.

TABLE I

THE PARAMETERS OF THE POWER DIVIDER (UNIT: mm)

D_1	D	W_s	W_c	W_{cpw}	W_{siw}	S	W_1	L_1
0.3	0.3	0.1	0.1	0.3	2.4	0.4	1.35	2.6

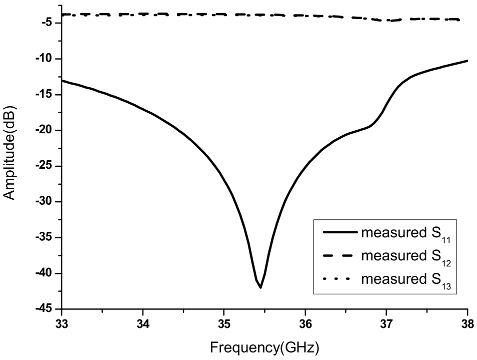


Fig 2. The simulated return loss of the power divider

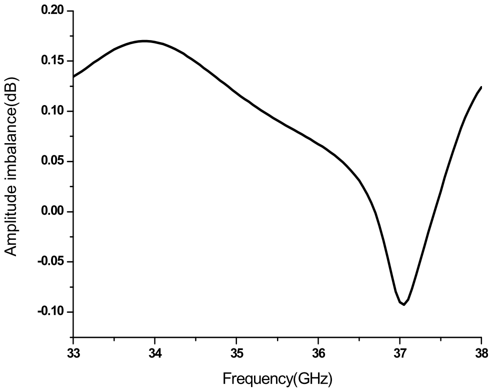


Fig 3. The amplitude imbalance of the power divider

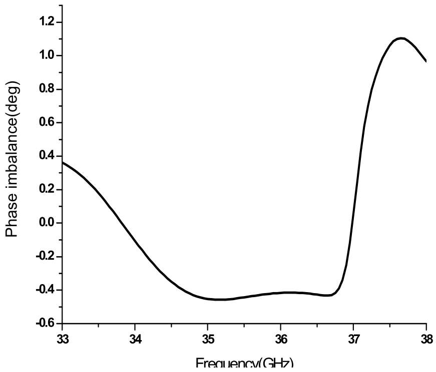


Fig 4. The phase imbalance of the power divider

III. ANTENNA ARRAY DESIGN

As shown in Fig. 5, the proposed antenna array is composed of 2×2 SICs and a compact four-way power divider mentioned above. The attracting design consideration here is that the SIC elements are arranged interdigitally in the middle of the two feeding SIW based on the feeding networks, which can make the structure much more compact.

This unique design could reduce the width by approximate 25% comparing with the traditional structure. Besides, the length can also be reduced in some degree by adopting the mentioned CPW-fed power divider. Moreover, this design method will exhibit great advantage, especially when the number of the SIC increases. In traditional design method for the SIW cavity antenna array, the feeding structure will become more complex when more SICs are added, therefore the whole

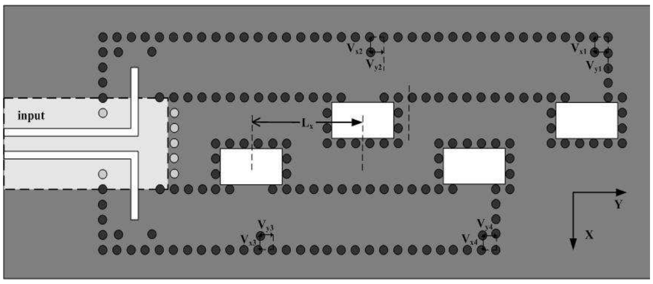


Fig 5. Geometry of the proposed antenna array

size of the antenna array will become very large. Through applying the method introduced in this design, it is easy to increase the SIC number by just lengthen the feeding SIW without changing the feeding structure at all.

To make the power entering into four SICs in-phase, the distance L_x between two adjacent SICs should be nearly waveguide wavelength λ_g. According to [10]:

$$\lambda_g = \frac{\lambda_s}{\sqrt{1-(\frac{\lambda_s}{2W_e})^2}} \qquad (1)$$

$$\lambda_s = \frac{\lambda_0}{\sqrt{\varepsilon_r}}, W_e = W_{siw} - \frac{D^2}{0.95S} \qquad (2)$$

Since the length of the SIC, a, is longer than that of λ_g, L_x has to set approximately $2\lambda_g$. As a result, the final optimized distance between the adjacent elements is 8.2 mm（0.95 λ_0), where λ_0 is the wavelength at 35GHz in the free space.

Besides, four vias are adjusted to ensure the power entering into four SICs in-phase. After optimizing with the HFSS, the proposed antenna array is fabricated. Fig. 6 shows the photograph of the proposed antenna array operating at 35 GHz. TABLE. II lists the parameters of the antenna array structure.

Fig. 7 gives the result of the simulated and measured S_{11} result of the antenna array. It can be observed that the frequency range for S_{11}<-10dB is 33.3-38.0 GHz(13.1%). The measured result shows well agreement with the simulated one.

The simulated radiation patterns at 35GHz are depicted in Fig. 8. The radiation pattern follow the trend depicted in [5] but low level of the side lobe in the E-plane is obtained. This may attribute to the decreasing radiation loss from the slotline.

Fig 6. Photograph of the antenna array.

TABLE II

THE PARAMETERS OF THE ANTENNA ARRAY (UNIT: mm)

Vx1	Vy1	Vx2	Vx2	Vx3	Vy3	Vx4	Vy4	L_s
0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.4	8.2

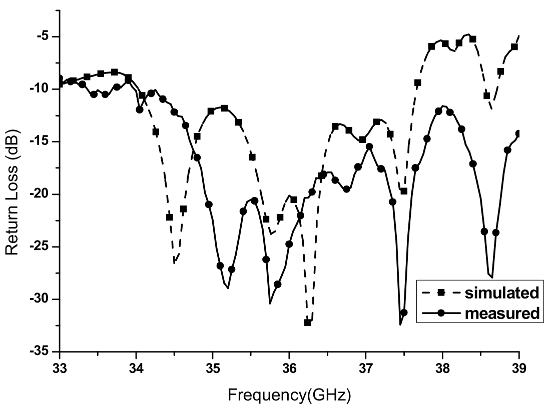
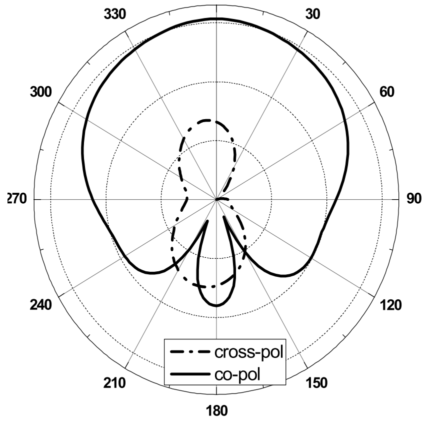
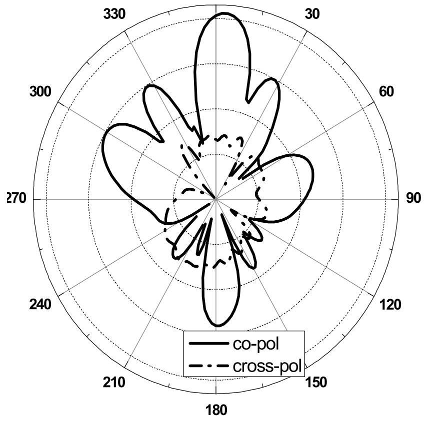


Fig 7. The simulated and measured return loss of the antenna array



(a) E-plane



(b)H-plane

Fig 8. The simulated radiation patterns of the antenna array at 35GHz.

IV. CONCLUSION

In this paper, a compact wideband SIW interdigital cavity antenna array has been proposed. By using the CPW-fed power divider, the SICs can be arranged in a more compact way comparing with the traditional design method. Therefore this antenna array can be fabricated in a smaller PCB board while keeping the good capacities in impedance width and the gain. This technology exhibits much more advantages when the number of the elements increases, thereby it is promising for high gain antenna in millimeter-wave applications.

REFERENCES

[1] J. Hirokawa and M. Ando, “Efficiency of 76-GHz post-wall waveguide-fed parallel-plate slot arrays,” *IEEE Trans. Antenna Propag.*, vol. 48, no. 11, pp. 1742-1745, Nov. 2000.

[2] Y. J. Cheng, W. Hong, and K. Wu, “Millimeter-wave substrate integrated waveguide multibeam antenna based on the parabolic reflector principle,” *IEEE Trans. Antenna Propag.*, vol. 56, no. 9, pp. 3055-3058, Sep. 2008.

[3] P. Chen, W. Hong, Z. Q. Quai, J. F. Xu, H. M. Wang, J. X. Chen, H. J.Tang, J. Y. Zhou, and K. Wu, “A multibeam antenna based on substrate integrated waveguide technology for MIMO wireless communications,” *IEEE Trans. Antenna Propag.*, vol. 57, no. 6, pp. 1813-1821, Jun. 2009.

[4] S. Cheng, H. Yousef, and H. Kratz, “79 GHz slot antenna based on substrate integrated waveguides (SIW) in a flexible printed circuit board,” *IEEE Trans. Antenna Propag.*, vol. 57, no. 1, pp. 64-71, Jan. 2009.

[5] Y. Zhang, Z. N. Chen. X. M. Qing, and W. Hong, “Wideband millimeter-wave substrate integrated waveguide slotted narrow-wall fed cavity antenna for 60-GHz,” *IEEE Trans. Antenna Propag.*, vol. 59, no. 5, pp. 1488-1496, May. 2011.

[6] Germain. S, D. Deslandes, K. Wu, “Development of substrate integrated waveguide power dividers,” *IEEE Conf on Electrical and Computer Engineering. Canadian*, vol. 3, 4-7, May 2003.

[7] C. H. Wang, Y. S. Lin. M. C. Tsai, C. Huai, and C. H. Chen, “An input-impedance-based circuit model for coplanar waveguide-to-slotline T-junction,” *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 6, pp. 1585-1590, Jun. 2004.

[8] F. F. He, K. Wu. W. Hong, H. J. Tang, H. B. Zhu and J. X. Chen, “A planar magic-T using substrate integrated circuits,” *IEEE Micro. Wireless Compon. Lett.*, vol. 18, no. 6, pp. 386-388, June. 2008.

[9] K. Gong, Z. N. Chen. X. M. Qing, P. Chen, and W. Hong, “Substrate integrated waveguide cavity-backed wide slot antenna for 60-GHz Bands,” *IEEE Trans. Antenna Propag.*, vol. 60, no. 12, pp. 6023-6026, Dec. 2012.

[10] Pozar D M. *Microwave engineering,3rd*. New York: Wiley, 2004.