Design of a Millimeter-Wave Frequency-Scanning Slot Array Antenna in SIW Technology

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***Abstract*— In this paper, design and implementation of a frequency-scanning slot array antenna in the 28 to 32 GHz frequencies, has been presented. The feeding network of the proposed array is based on a meander Surface Integrated Waveguide (SIW) which is fabricated by low-cost Printed Circuit Board (PCB) technology. The antenna has a narrow fan beam with a beamwidth of 10 degrees in azimuth, realized gain of 10 dBi and Side Lobe Level (SLL) of better than -10 dB. The antenna is able to cover the scan area of 90 degrees by frequency sweep with a rate of 10 degree/ 400 MHz.**

Keywords—slot array antenna, substrate integrated waveguide (SIW), beam steering, frequency-scanning antenna

I. Introduction

In a wide range of radar and imaging applications, the goal is to acquire precise real-time information about objects in space like their position and velocity which requires a narrow beam antenna with electrically scanning capability. In this article, we attempt to design an array of antennas to develop a frequency-scanning fan beam that is applicable in 3D imaging systems. By implementing an array of antennas, we are able to achieve a narrow beam with frequency-scanning capability; the phase between elements changes by sweeping the frequency, so the beam steers and can cover a wide range of angles. The spatial distance between two adjacent elements should be half free-space wavelength and the elements must feed in-phase to achieve a broadside radiation [1]. On the other hand, design of proper array feeding network is challenging, because making exact phase difference between two adjacent elements is difficult and usually costly to achieve. Moreover, in some structures the mutual coupling between elements poses its own challenge.

Slot array antenna which fed by SIW structure is a good choice for this purpose. SIW technology combines the advantages of planar technologies and classical metallic waveguides. The most significant advantage of the SIW technology is the possibility to integrate a complete system in a single substrate. Moreover, SIW circuits can be easily connected to microstrip lines and coplanar waveguides, realized in the same substrate [2]. There are many surveys in literature regarding SIW slot array antennas [2]. They are similar to classical slotted-waveguide antennas and can be designed by utilizing the method developed in [3]. These antennas have been designed for different frequency bands from microwave to millimeter-wave regime [4-6]. Circularly polarized SIW antenna has been obtained in [7] by alternate rotation of slots. There are different types of feeding networks to excite the radiating slots with proper amplitude and phase as discussed in [8-11]. These feeding networks enable the modification of the amplitude and phase for each slot in the array, thus provide scanning capability for the direction of maximum radiation [2].

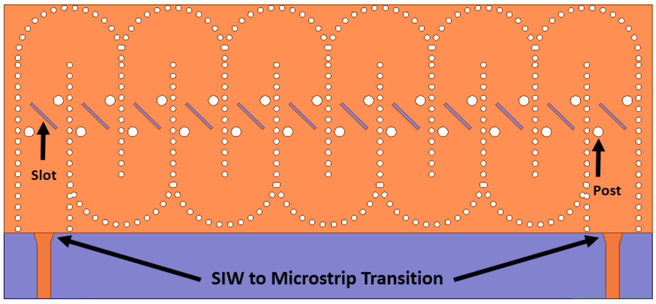


Fig. 1. The structure of the proposed antenna.

Fig. 1 shows the structure of the proposed antenna. It consists of a few slots that are fed by a meander SIW structure. The inductive posts are used to improve the impedance matching and compensate the effect of the slots. Simple tapered microstrip lines are designed to properly feed and terminate the SIW by microstrip line. The designing steps and the antenna properties will follow in the next section.

II. Design Procedure

A. SIW Structure

As illustrated in Fig. 1, the feeding network of the proposed slot array antenna is based on a SIW structure which can be approximated by an equivalent rectangular waveguide with proper width as [12]:

$$w_{eff} = w - \frac{d^2}{0.95s} \tag{1}$$

where w, w_{eff}, s and d are the width of SIW, width of approximated rectangular waveguide, distance between adjacent vias and via diameter respectively. Because of its geometrical structure, the only modes supported by SIW are the ones similar to TE_{n0} in conventional rectangular waveguides [2]. As for the rectangular waveguides, the bandwidth of the single-mode SIW is defined between $1.25f_c$ and $1.9f_c$, where f_c is the cut-off frequency of the TE_{10} mode [13], so we choose the center frequency of the antenna (f_0=30 GHz) as $1.5f_c$. By determining f_c, the width of approximated rectangular waveguide (w_{eff}) can be obtained by conventional rectangular waveguide relations and then, the width of the SIW (w) can be calculated by replacing w_{eff} in (1).

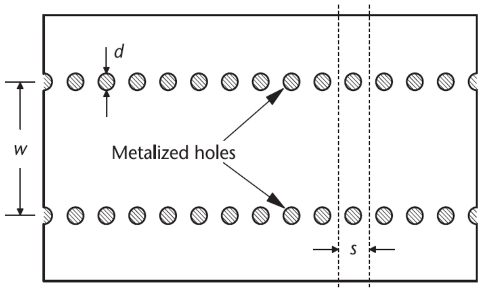


Fig. 2. SIW structure and design parameters [2].

If the distance between vias (s) and their diameters (d) are chosen properly, the energy leakage from two adjacent vias is negligible and the SIW works in guiding regime [2]. The typical design rules for these parameters are as [2]:

$$\frac{\lambda_c}{20} < s < \frac{\lambda_c}{4} \quad , \quad \frac{s}{2} < d < s \tag{2}$$

where λ_c is the cut-off wavelength of the SIW. In this work, we consider s and d as 1 *mm* and 0.5 *mm* respectively. The substrate used here, is a RO4003 with relative permittivity of 3.55 and the thickness of 0.508 *mm*.

B. Single-element Design

Fig. 3 shows one element of the slot array antenna. There is a relation in [14] that helps us to calculate the length of the slot (L) as:

$$L = \frac{\lambda_0}{\sqrt{2(\varepsilon_r + 1)}} \tag{3}$$

where λ_0 is the free-space wavelength and ε_r is the relative permittivity of the substrate. The slot has capacitive effect and does not match the SIW. To improve the impedance matching between them, two symmetric posts have been added near the slot that have inductive effect to compensate the undesirable effect of the slot [15]. There are 4 parameters shown in Fig. 3, helping designer to achieve the best impedance matching across the frequency band: posts diameter (D), position of the posts (X, Y), width of the slot (W) and rotation angle of the slot (α). We consider α as 45 degrees and start to optimize the other parameters. Fig. 4 shows the effect of these parameters on reflection coefficient of the single-element antenna. Finally, we choose the values written in Table I.

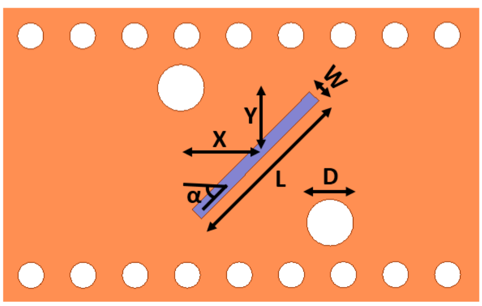


Fig. 3. One of the elements in the slot array antenna.

TABLE I. SINGLE-ELEMENT ANTENNA PARAMETERS

Variables	*W*	*D*	*X*	*Y*
Values (*mm*)	0.25	0.9	1.3	1.43

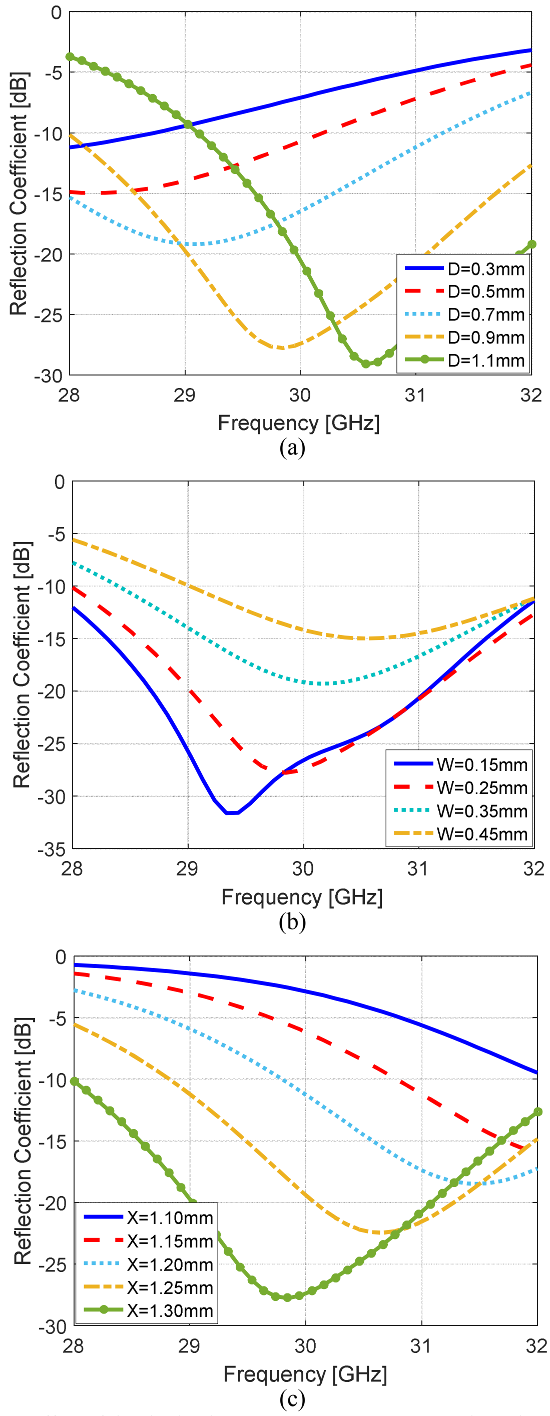


Fig. 4. Effect of the single-element antenna parameters on impedance matching. (a) D (b) W (c) X (Y=X+0.13*mm*).

C. Array Design

To decrease the array length, curved SIW sections are added to the antenna structure as shown in Fig. 1. Due to the curved sections, the polarization plane is tilted by 180 degrees in transition between adjacent slots [15], so for in-phase excitation, the electrical length between these two adjacent slots must be nπ where n is an odd number. Also, to

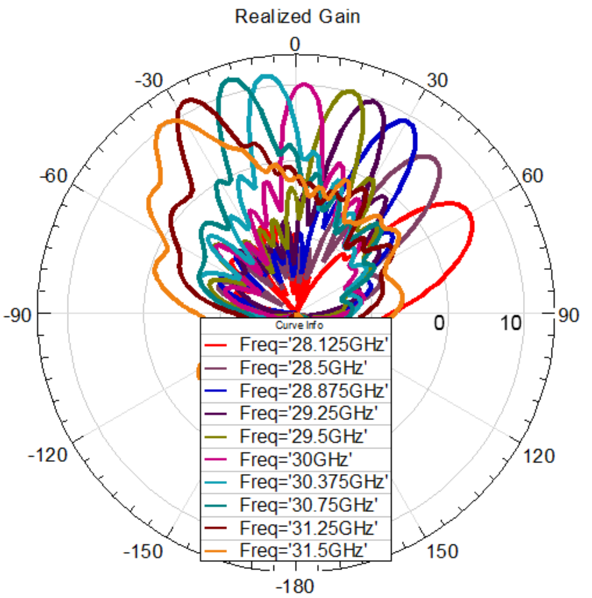


Fig. 5. Simulation results: Radiation pattern of the antenna in E plane.

have precise spatial spacing between the slots, the designer may add a few columns of vias near SIW walls between them or slightly change the width of the SIW.

There are two conventional ways for terminating the SIW; shortening the last section or matching it to a resistive load. If we short the end of the SIW, the reflected waves propagate in the SIW and radiate from the slots, producing spurs in radiation pattern. But if the last section is connected to a matched load, there will be no reflected waves or destructive effects on the radiation pattern.

The simplicity of using microstrip lines along with the similarity between modal fields, enabled the excitation and termination of the SIW structure to be done by a microstrip line. The tapered microstrip lines reducing the discontinuity effect, have been designed to match the 50 ohm microstrip line to the SIW. The width of the tapered lines at the SIW side can be computed using the method presented in [13]. Fig. 5 shows the simulation results of the proposed slot array antenna.

III. Construction and Measurement

The proposed antenna has been constructed by low cost, single-layer PCB technology. Fig. 6 shows the photograph of the proposed antenna with two 2.9 *mm* connectors, lunched to the antenna's ports. Return loss of the constructed antenna has been measured by a Keysight Vector Network Analyzer in anechoic chamber in an antenna laboratory. The measured reflection coefficient in comparison with the simulation result has been shown in Fig. 7. As shown, the measurement is in good agreement with the simulation. The radiation patterns in both E and H planes have been measured in the lab. Fig. 8 shows the measured patterns in different frequencies. As shown, the radiation pattern scans the azimuth angle while the frequency is changed. The scan rate is around 10 degree/400 MHz.

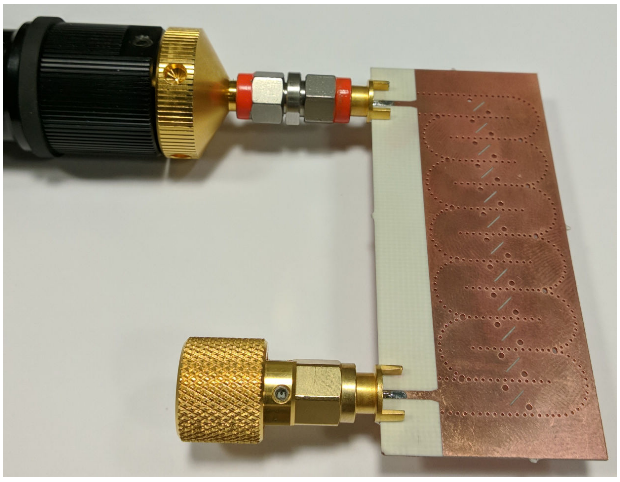


Fig. 6. Photograph of the implemented antenna.

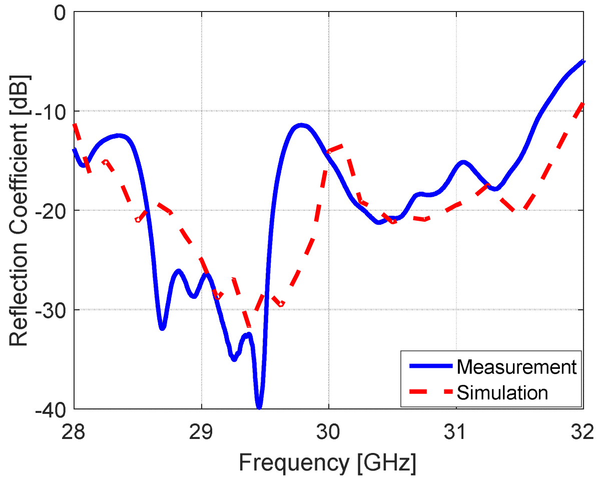
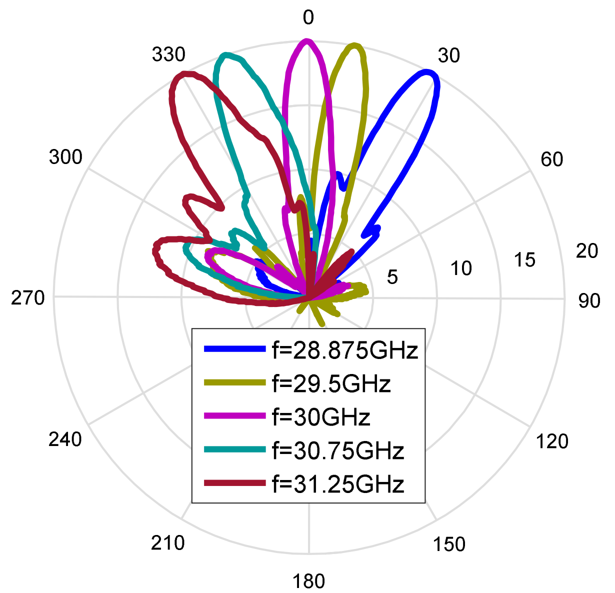
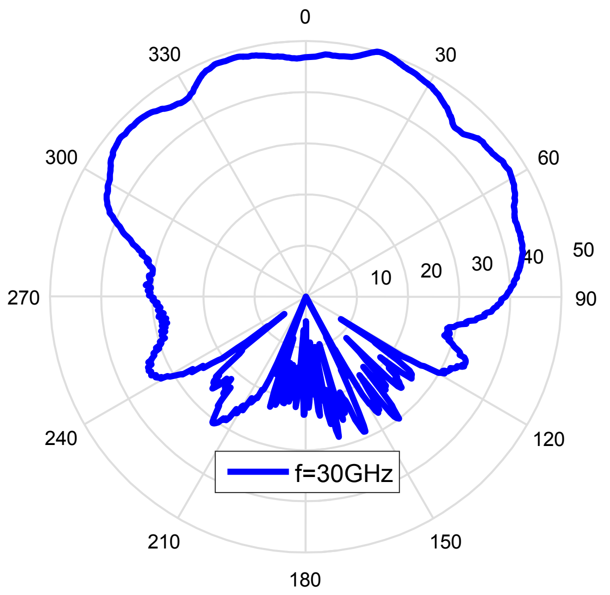


Fig. 7. Measured reflection coefficient in comparison with the simulation result.



(a)



(b)

Fig. 8. Measured radiation patterns of the antenna in (a) E plane and (b) H plane.

IV. Conclusion

In this paper we reported design, implementation and measurement results of a millimeter-wave slot array antenna in the SIW technology with frequency-steering capability. The feeding network of the array has been designed based on meander SIW structure and fabricated using PCB technology. Dimension of the proposed antenna is $30mm \times 70mm$ and has a narrow fan beam with a half-power beamwidth of 10 degrees, realized gain of 10 dBi and a SLL of better than -10 dB at the center frequency, capable of covering a range of 90 degrees in azimuth based on its feed frequency.

References

[1] R. S. Elliott, Antenna Theory and Design, Englewood Cliffs. NJ: Prentice-Hall Publishing Co., 1981.

[2] R. Garg, I. Bahl, and M. Bozzi, Microstrip Lines and Slotlines, 3rd ed., Artech House, pp.497–567, 2013.

[3] R. S. Elliott, “An improved design procedure for small arrays of shunt slots,” IEEE Trans. Antennas Propagat., vol. 31, pp. 48–53, 1983.

[4] L. Yan, et al. “Simulation and experiment on SIW slot array antennas,” IEEE Microwave Wireless Comp. Lett., vol. 14, pp. 446–448, 2004.

[5] K. K. Samanta, D. Stephens, and I. D. Robertson, “60 GHz multi-chip-module receiver with substrate integrated waveguide antenna and filter,” Electron. Lett., vol. 42, pp. 701–702, 2006.

[6] D. Stephens, P. R. Young, and I. D. Robertson, “W-band substrate integrated waveguide slot antenna,” Electron. Lett., vol. 41, pp. 165–167, 2005.

[7] P. Chen, et al., “A substrate integrated waveguide circular polarized slot radiator and its linear array,” IEEE Antennas Wireless Propagat. Lett., vol. 8, pp. 120–123, 2009.

[8] Y. J. Cheng, et al., “Substrate integrated waveguide (SIW) Rotman lens and its Ka-band multibeam array antenna applications,” IEEE Trans. Antennas Propagat., vol. 56, pp. 2504–2513, 2008.

[9] P. Chen, et al., “A double layer substrate integrated waveguide Blass matrix for beamforming applications,” IEEE Microwave Wireless Comp. Lett., vol. 19, pp. 374–376, 2009.

[10] C. J. Chen, and T. H. Chu, “Design of a 60–GHz substrate integrated waveguide Butler matrix—A systematic approach,” IEEE Trans. Microwave Theory Tech., vol. 58, pp. 1724–1733, 2010.

[11] T. Djerafi, N. J. G. Fonseca, and K. Wu, “Planar Ku-band 4×4 Nolen matrix in SIW technology,” IEEE Trans. Microwave Theory Tech., vol. 58, pp. 259–266, 2010.

[12] Y. Cassivi, et al., “Dispersion characteristics of substrate integrated rectangular waveguide,” IEEE Microwave Wireless Comp. Lett., vol. 12, pp. 333–335, 2002.

[13] D. Deslandes, “Design equations for tapered microstrip-to-substrate integrated waveguide transitions,” IEEE MTT-S International Microwave Symposium Digest (IMS), Anaheim, CA, pp. 704–707, 2010.

[14] H. Lu, and T. Chu, "Equivalent circuit of radiating longitudinal slots in substrate integrated waveguide," in Antennas and Propagation Society International Symposium, 2004.

[15] A. Shoykhetbrod, D. Nüßler, and A. Hommes, “Design of a SIW meander antenna for 60 GHz applications,” in German Microwave Conference (GeMic), 2012.