Design of Rotman Lens Antenna at Ku-Band Based on Substrate Integrated Technology

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***Abstract-* In this research work, a multibeam antenna which is a combination of a beamformer network (BFN) and a linear array antenna, has been designed. A Rotman lens has been chosen as beamformer network and Vivaldi antennas have been selected for constructing array antenna. The Substrate Integrated Waveguide (SIW) was used for implementing Rotman lens. After explanation the structure of Substrate integrated waveguide, a prototype SIW Rotman lens was designed to create 7 beams at angles of 0°, ±10°, ±20° and ±30°. Each beam is corresponding to one of the input port of Rotman lens. This Rotman lens was designed for aeronautical applications and operates at center frequency of 16 GHz and frequency bandwidth of 1 GHz. It was found that the amplitude and phase distributions at output ports of Rotman lens are appropriate. Then a linear array of 7 Vivaldi antennas was connected to the Rotman lens to realize the multibeam Rotman lens antenna.**

Index Terms- Beam steering, microwave lens, Rotman lens antenna, substrate integrated waveguide

I. INTRODUCTION

In many communication and radar applications it is needed to have antennas that create multiple beams in several directions or scan a beam spatially. Phased array antenna is an alternative approach for such applications [1]. Phased arrays can be fed via several ways. One of the simplest methods for feeding them is embedding a microwave lens between transceiver and array. The microwave lens is one of the low cost, low profile and light instrument for feeding phased arrays. Many different types of lenses are available; but "Rotman" lens is the best among them; because it has compact size and easily attached to a linear array [1].

Rotman lens is a multi-input, multi-output network. The input and output ports are called "beam port" and "array port" and the array ports are connected to the array elements through transmission lines. The schematic of Rotman lens antenna is shown in Fig. 1. If one of the beam ports is excited, the electromagnetic wave will be emitted in the cavity space and reaches to array ports. The shape of contour that array ports have laid on it and the length of transmission lines are determined so that, a progressive phase taper is created on array elements; and thus a beam is formed at a particular

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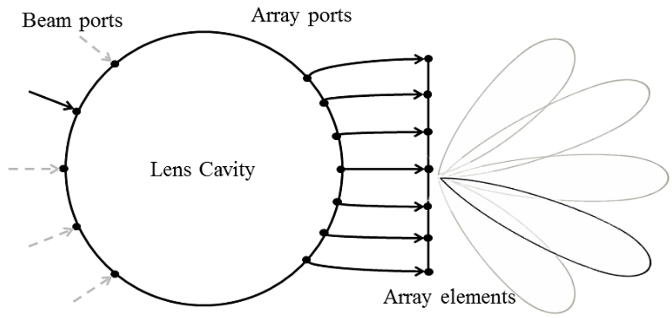

Fig. 1. Schematic of Rotman lens antenna

direction in the space. If another beam port is excited, the phase taper on the array elements will be changed and the beam will be created at another direction [2].

Rotman lens is used in situations that small and lightweight antenna with beam scanning ability is required. Some practical applications of the Rotman lens antenna are: Mounting on Aircraft's nose for Electronic Counter Measure (ECM), using as Unmanned Aerial Vehicle (UAV) antenna and also for artificial vision of vehicles, etc.

Up to now, different kinds of Rotman lenses such as metallic waveguide lens and microstrip lens have been introduced [3], [4]. Recently, one kind of transmission line, called Substrate Integrated Waveguide (SIW) was introduced. SIW structures combine the advantages of lightweight and low cost fabrication of printed circuit and the low loss characteristic of closed structures. In addition, SIW can easily be integrated with all the planar circuits [5].

To the author's knowledge, a little works have been devoted to the Rotman lens antenna based on SIW structure; and in that little works the design equations of this kind of lens have been mentioned incompletely. The main goal of this paper is to present the complete design equations of SIW Rotman lens. Then, a prototype SIW Rotman lens that feeds an array of Vivaldi antennas is proposed. A basic overview of the lens-design consideration, as originally developed by Rotman [2], is presented in the part A of Section II and for SIW application, a few changes have been applied in those equations. In part B of this section, the design method of SIW with particular cutoff frequency has been explained. A prototype Rotman lens at substrate integrated technology will be designed in part C of section II. Finally, an array of Vivaldi antennas have been added to lens in section III and output patterns of Rotman lens antenna have been shown.

II. DESIGN OF SIW ROTMAN LENS

A. Theory of Rotman Lens

For designing a Rotman lens we must obtain the perfect place for the beam ports and array ports, and appropriate length for transmission lines between array ports and array elements. As shown in Fig. 2 Rotman lens has three main contours C_0, C_1 and C_2 which are called "focal arc", "array contour" and "outer contour" and the beam ports, array ports and array elements are placed on them

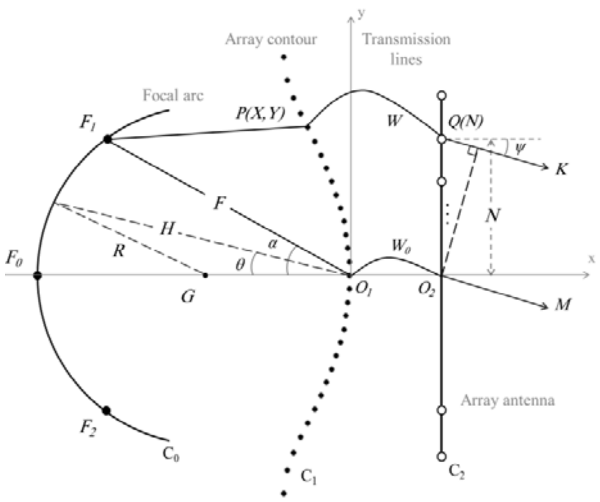

Fig. 2. Parameters of Rotman lens antenna

respectively. In Rotman lens the outer contour is a straight line and the locations of array elements on it, which are called *Q(N)*, are determined by the distance *"N"* relating to the origin *"O_2"*. Array contour is defined by a set of points $P(X,Y)$ relating to origin *"O_1"* and its shape will be obtained by lens design equations. Each point $P(X,Y)$ is connected to its corresponding point *Q(N)* by a transmission line of length *"W"*; and *"O_1"* is connected to *"O_2"* by a transmission line of length *"W_0"* [2].

The focal arc is a sector of the circle that passes through focal points of Rotman lens [2]. As shown in Fig. 2, Rotman lens has three focal points F_0, F_1 and F_2 with $(-G, 0)$, $(-F\cos\alpha, F\sin\alpha)$ and $(-F\cos\alpha, -F\sin\alpha)$ coordinates [6]. *"F"* and *"G"* are the off axis and on axis focal length and "α" is the focal angle. The beam ports can be located at any angle "θ" of focal arc to produce a beam at angle "ψ" in space. It assumes that 0, ψ_α and $-\psi_\alpha$ are the angles of beam directions corresponding to focal points F_0, F_1 and F_2.

Suppose that three point sources are located on three focal points of Rotman lens and two rays emit from each source; which one of them passes through FO_1O_2M path and another ray passes through *FPQK* path. Electrical length of two rays must be equal for all sources. Thus in general three equations are obtained ((1)–(3) of [2]). The difference between design equations of various types of Rotman lenses appears from this step. In [2] the lens cavity is a parallel plate region and the transmission lines are coaxial cables, so the TEM wave is emitted in them and the wave has equal phase constant (β) in cavity, transmission lines and free space. Thus the phase constant is omitted from all equations. Equation (1) of [2] is represented here for instance:

$$\left(\overrightarrow{F_1P}\right) + W + N\sin\psi_\alpha = F + W_0 \qquad (1)$$

In SIW lenses the condition is different; because the mode of waves in cavity, transmission lines and free space are TEM, TE_{10} and TEM (with different phase constant compared with cavity) respectively. Since they have different phase constant, in three principal equations each path length must be multiply with phase constant of wave in that path. So the first equation must be modified as follows:

$$\begin{aligned}&\overline{(F_1P)}\beta'_{TEM}+W\,\beta_{TE10}+N\,\sin\psi_\alpha\beta_{TEM}\\&=F\,\beta'_{TEM}+W_0\beta_{TE10}\end{aligned} \tag{2}$$

Where β'_{TEM} and β_{TEM} are the phase constants of TEM wave in dielectric space and free space respectively. By simplifying (2), the following equation is obtained.

$$\overrightarrow{(F_1P)}\sqrt{\varepsilon_r}+W\,\sqrt{\varepsilon_{eff}}+N\,\sin\psi_\alpha=F\,\sqrt{\varepsilon_r}+W_0\sqrt{\varepsilon_{eff}} \tag{3}$$

Where ε_r is the relative dielectric constant of the substrate and ε_{eff} is the effective dielectric constant of the SIW transmission line and obtained from (4).

$$\varepsilon_{eff}=\varepsilon_r\left(1-\left(\frac{f_c}{f}\right)^2\right) \tag{4}$$

Similarly, the two other principal equations are obtained. By definition some variables such as the ratio of on axis to off axis focal length (g), the normalized coordinate of array elements on outer contour (η) and normalized length of transmission lines (w) in (5), these three equations are simplified and three new equations will be derived.

$$a_1=\cos\psi_\alpha\qquad b_1=\sin\psi_\alpha\qquad g=\frac{G}{F}\qquad \eta=\frac{1}{\sqrt{\varepsilon_r}}\frac{N}{F}\qquad w=\sqrt{\frac{\varepsilon_{eff}}{\varepsilon_r}}\frac{W-W_0}{F} \tag{5}$$

Next, other three equations are derived directly from the geometry of Fig. 2 which express the length of F_1P, F_2P and F_0P lines in terms of lens dimensions ((4)–(6) of [2]). Similarly, these equations can be simplified by definition following variables:

$$a_0=\cos\alpha\qquad b_0=\sin\alpha\qquad x=\frac{X}{F}\qquad y=\frac{Y}{F} \tag{6}$$

As mentioned in [2] by combining these six equations, finally, the main three design equations can be obtained ((7)–(9)):

$$aw^2+bw+c=0 \tag{7}$$

$$y=\frac{b_1}{b_0}\eta(1-w) \tag{8}$$

$$x=\frac{-1}{(g-a)}\left((\mathrm{g}-1)w+0.5\eta^2b_1^2\right) \tag{9}$$

Where a, b and c are functions of a_0, b_0, b_1, g and η that can be obtained easily. Equations (7)-(9) will be used in the next section for calculating the (x,y) coordinate of array ports and the w lengths of

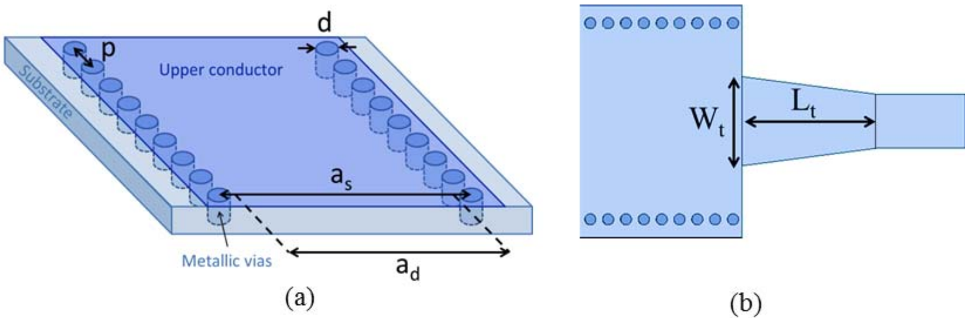

Fig. 3. (a) Structure of the Substrate Integrated Waveguide (SIW). (b) Transition between microstrip line and SIW.

transmission lines. As defined in [2], the path length error *"ΔL"* is the difference between electrical lengths of rays passing through point O_1 and the rays passing through point *P*; and *"Δl"* is the path length error that has been normalized to *F*:

$$\Delta l = \frac{\Delta L}{F} = \sqrt{\varepsilon_r}\left(h^2 + x^2 + y^2 + 2hx\cos\theta - 2hy\sin\theta\right)^{\frac{1}{2}} - \sqrt{\varepsilon_r}h + \sqrt{\varepsilon_r}w + \sqrt{\varepsilon_r}\eta\sin\psi \tag{10}$$

Where, $h=H/F$ and the *H* parameter is shown in Fig. 2. For fixed θ, Δl is a function of η and there is no phase deviation ($\Delta l = 0$) when the beam port is placed at one of the focal points [2].

B. Substrate Integrated Waveguide

The beam and array ports of Rotman lens and the transmission lines between array ports and array element are implemented in substrate integrated technology. Therefore, before addressing the issue of SIW Rotman lens, the overall structure of SIW must be explained.

In substrate integrated technology, non-planar microwave structures such as metallic waveguides can be fabricated in planar form by embedding several rows of periodic metallic via holes in substrate as metallic walls of that structures; and covering the top of them by metallic plates. SIW that shown in Fig. 3(a) is the most popular structure in substrate integrated technology; and can be modeled by an equivalent dielectric filled waveguide with same height and different width. If the diameters of metallic via holes and the center to center distances of adjacent via holes are selected as *"d"* and *"p"* respectively; the relation between widths of SIW and equivalent waveguide can be obtained from (11) [7].

$$a_d = a_s - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{a_s} \tag{11}$$

Where, a_s and a_d are the widths of SIW and equivalent dielectric filled waveguide respectively. The characteristics of SIW and equivalent waveguide, such as dominant mode (TE_{10}), cutoff frequency, guided wavelength and dispersion characteristic (α and β) are the same [7].

The transition structure between microstrip line and SIW is another key part of design, to achieve an appropriate reflection coefficient at beam ports and array ports. See Fig. 3(b). A general method for calculating the width and length of transition part (W_t and L_t) is proposed in [8]. Then, the obtained

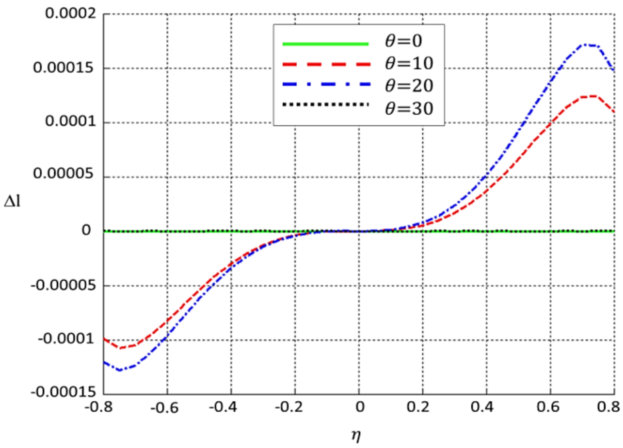

Fig. 4. Normalized path length error of Rotman lens (g=1.125, α=30)

values must be used as initial points in an optimization procedure by using of a full-wave simulator such as CST or HFSS.

C. Design Procedure of SIW Rotman Lens at Ku-Band

An SIW Rotman lens is realized on Rogers RT/duroid 5880 substrate with ε_r = 2.2 and 31 mil thicknesses, which operates at center frequency of 16 GHz and produces 7 beams in the range of –30° to 30°. Unlike microstrsip Rotman lens, in SIW Rotman lens the beam and array ports have broad width; so the distance between adjacent beam ports and adjacent array ports must be determined such large that, the neighbor waveguides don't interfere with each other. Therefore for designing an SIW Rotman lens, we should first calculate the width of input and output SIW ports.

The width of equivalent waveguide is chosen so that the desired cutoff frequency is achieved (a_d = 8.5 mm). Due to the practical limits of fabrication, the d and p are selected 0.5 mm and 0.8 mm. Now, the width of SIW can be calculated by solving (11) (a_s = 8.8 mm).

Also, the dimentiones of transition between microstrip line and SIW are achieved by a full-wave simulation with CST software and the results are W_t = 2.7 mm and L_t = 4.23 mm.

After calculating the width of SIW, we can design the Rotman lens. The lens design starts by choosing the values of design parameters, focal angle (α), the angle of off axis focal points beam (ψ_α), on axis to off axis focal length ratio (g) and the normalized coordinate of array elements on outer contour (η).

An arbitrary value can be selected for α; but the impact of the value of α on the shape of focal arc and array contour must be considered. If an appropriate value is not selected for α, the lens shape will be unbalanced and the lens will not work correctly [9]. In this project focal angle set to 30°. And the angle of created beam, when a beam port is located on off-axis focal point is set to 30° too ($\alpha = \psi_\alpha$). The beam ports are located at angles of 0°, ±10°, ±20° and ±30° on focal arc. These locations are appropriate for embedding designed SIW at them. Next the value of g must be determined. As explained in [2] the optimal value of g is calculated from (12).

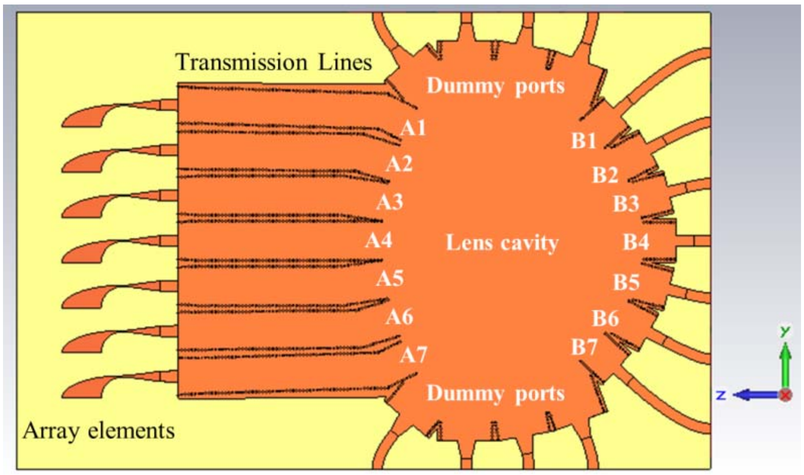

Fig. 5. The modified SIW Rotman lens antenna. The ports that have been named with B and A are the beam ports and array ports respectively.

$$g = \frac{G}{F} = 1 + \frac{\alpha^2}{2} \tag{12}$$

The value that obtained from (12) is g = 1.137; but another value of g can be selected by use of Δl vs. η graphs (Fig. 4). By changing the value of g, the path length error also changes and the maximum value of Δl should not exceed the allowable value. By changing the value of g in addition to these graphs, the shape of focal arc and array contour are changed too [9]. According to the maximum allowable value of Δl and to achieve a balanced shape of lens, two important parameters must be determined in this step: g and η_{max}. With possession the η_{max}, the normalized coordinates of array elements are calculated from (13):

$$\eta = -\eta_{max} < \frac{\eta_{max}}{(NE - 1)/2} > \eta_{max} \tag{13}$$

By determination the α, ψ_α, g and η the amounts of w, x and y can be calculated from (7)–(9) and the actual values of w, x and y (W , X and Y) must be obtained by multiplying the off axis focal length F at them. Now we must select an appropriate value for F. The minimum amount of F is calculated from (14) [5].

$$F_{min} = \frac{1}{\sqrt{\varepsilon_r}} \frac{N_{max}}{\eta_{max}} = \frac{1}{\sqrt{\varepsilon_r}} \frac{(NE - 1)d}{2\eta_{max}} \tag{14}$$

If a small value is selected for η_{max} the phase error will be reduced. But according to (14), the small amount of η_{max} causes the enlargement of focal length F; and then the spillover loss is increased; and vice versa. Based on the above contents, g = 1.125 and η_{max} = 0.75 are chosen and from (14), F_{min} = 32.7 mm. Then we set F = 59 mm.

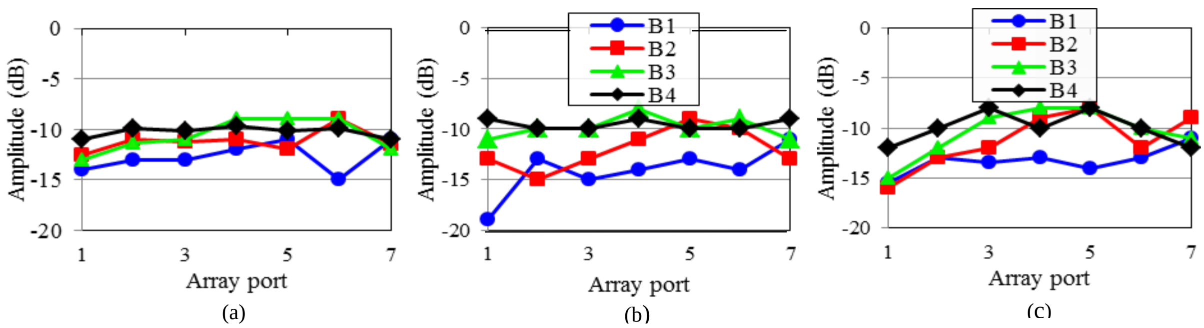

Fig. 6. Array ports amplitude distribution for beam ports B1, B2, B3 and B4 for three frequencies (a) 15.5 GHz, (b) 16 GHz (c) 16.5 GHz.

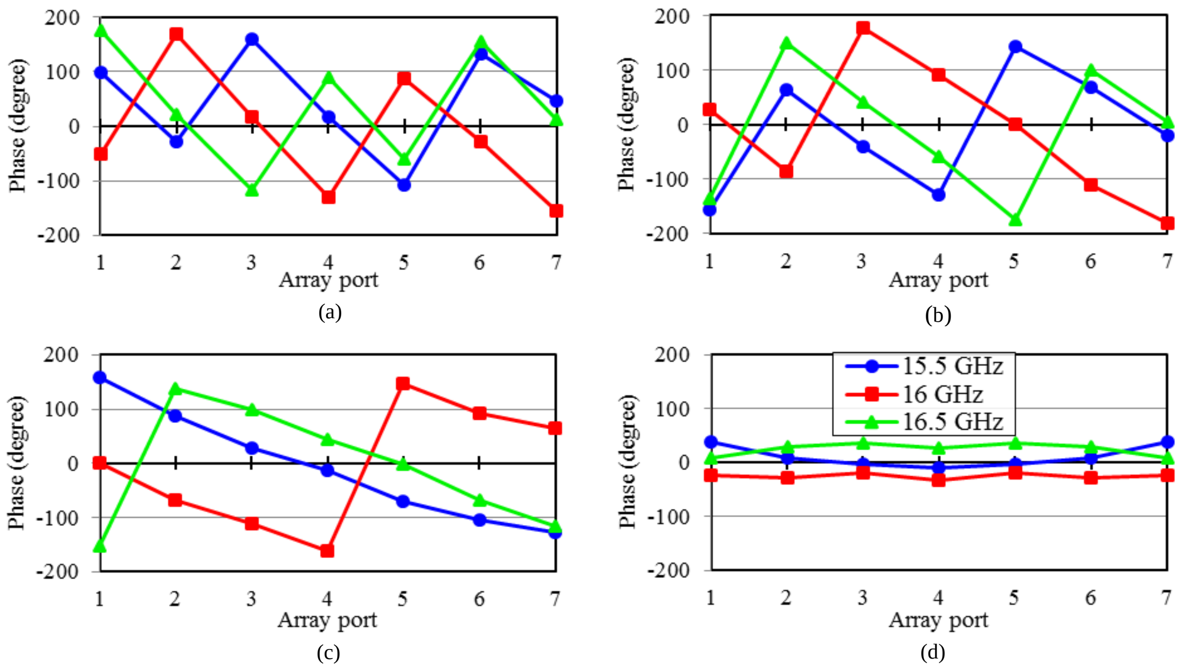

Fig. 7. Array ports relative phase distribution for three frequencies when the beam ports (a) B1, (b) B2, (c) B3 and (d) B4 are excited.

The design and implementation of transmission lines with phase shifters in SIW technology is the next step. In SIW the phase shifters are realized by increasing or decreasing the width of SIW. The last step is inserting dummy ports at blank spaces in sides of lens, between focal arc and array contour. The dummy ports decrease the reflections from sides of lens. Reflections from sides increase the side lobe level of pattern. In order to improve phase and amplitude at array elements, some corrections must be applied to lens shape. One of the main factors that corrupt the lens results such as S-parameters and amplitude distribution on array elements is reflection from metallic vias of dummy ports. To resolve this issue, dummy ports are shifted slightly to the back. The final scheme of Rotman lens can be seen in Fig. 5 and the amplitude and phase distribution on array elements for three frequencies 15.5, 16 and 16.5 GHz are plotted in Fig. 6 and Fig. 7. As shown in these figures the level of amplitude is acceptable and the phase distribution is linear whit different progressive phase for each beam port.

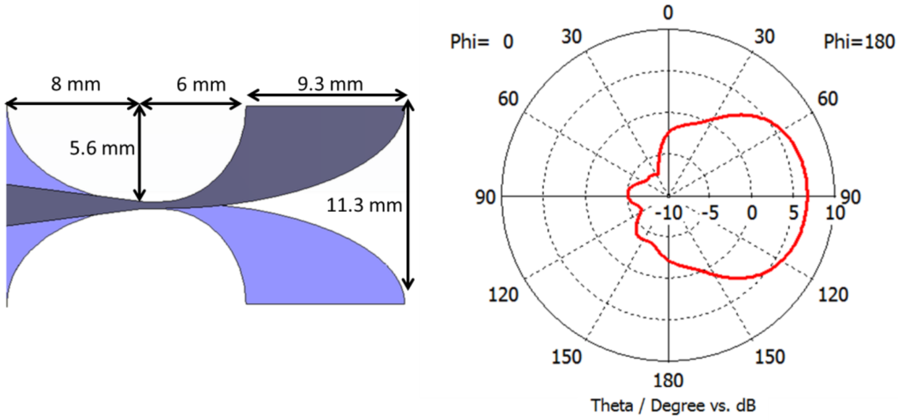

Fig. 8. Vivaldi antenna for 16 GHz and its E-plane pattern.

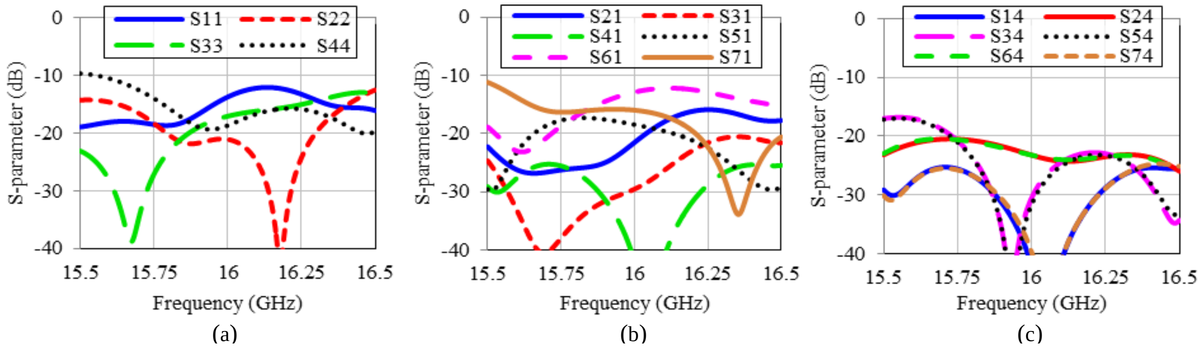

Fig. 9. (a) Reflection coefficients of B1 to B4 beam ports. The coupling between beam ports when (b) B1 and (c) B4 are excited.

III. SIW ROTMAN LENS ANTENNA

After designing SIW Rotman lens a Vivaldi antenna that shown in Fig. 8 is designed for using as elements of array antenna. Vivaldi antenna has wide frequency band; so we use this kind of antenna for observing the patterns of Rotman lens antenna and verifying the lens design. Then we only need to attach lens and array together to achieve a Rotman lens antenna. We use CST Microwave Studio and Ansoft HFSS to simulate this antenna. As shown in Fig. 9(a) reflection coefficients of all the beam ports in entire frequency band are below -10 dB. As an example, the mutual coupling of the edge beam port B1 and center beam port B4 with other beam ports at frequency band 15.2 to 16.8 GHz are shown in Fig. 9(b)-(c). As can be seen in Fig. 9(b) due to the reflection from vias of array ports the mutual coupling between B1 and B7 is more than mutual coupling between B1 and B2. The patterns of antenna for three frequencies 15.5, 16 and 16.5 GHz, which obtained from CST and HFSS simulators, can be seen in Fig. 10 and Fig. 11 respectively. It can be seen that for 16 GHz, the main beams of beam ports B1 to B4 are placed at angles 30°, 20°, 11° and 0° in space and the 3-dB beam widths of them are 16.6°, 11.7°, 11.5° and 10.9° respectively. According to the theory of phased array as the beam is moving away from the broadside angle, the beamwidth increases, and thus the gain of beam decreases. As can be seen in Fig. 10 and Fig. 11 the results of two softwares are similar.

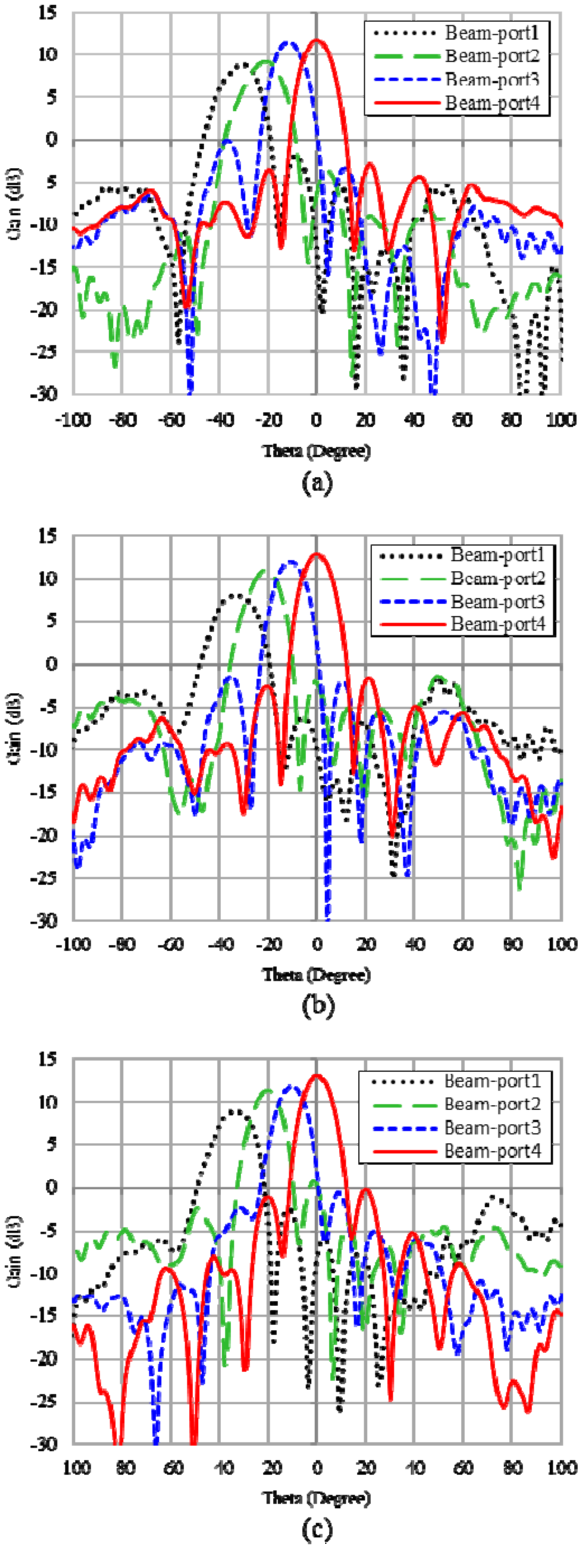

Fig. 10. E-plane radiation patterns of SIW Rotman lens antenna at YOZ plane for (a) 15.5 GHz, (b) 16 GHz and (c) 16.5 GHz. (simulated in CST)

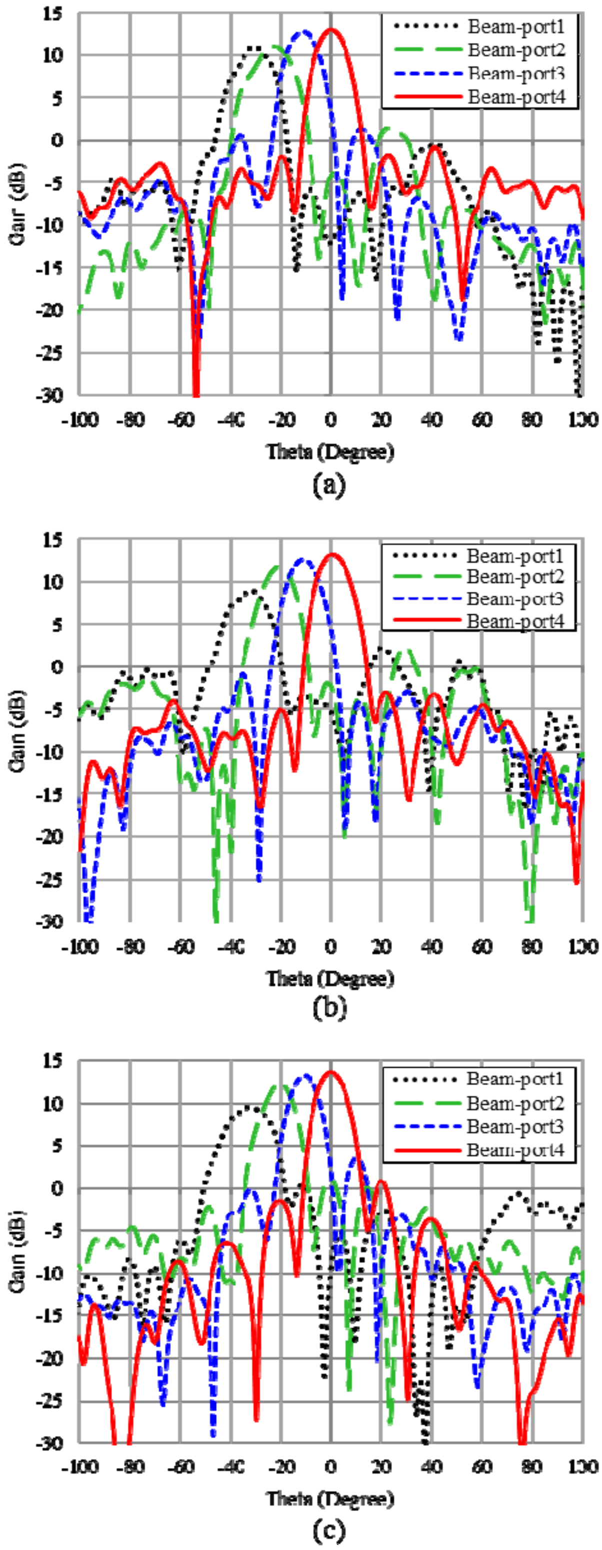

Fig. 11. E-plane radiation patterns of SIW Rotman lens antenna at YOZ plane for (a) 15.5 GHz, (b) 16 GHz and (c) 16.5 GHz. (simulated in HFSS)

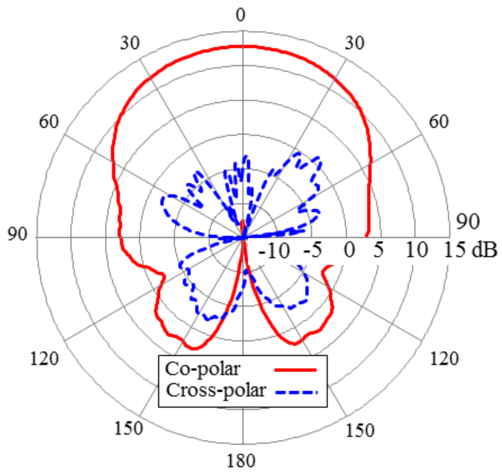

Fig. 12. Co-polar and Cross-polar radiation patterns of beam-port4 of SIW Rotman lens antenna at XOZ plane for 16 GHz. (simulated in CST)

Also, the co-polar and cross-polar E-field patterns of port B4 of antenna at XOZ plane for center frequency are illustrated in Fig. 12.

IV. CONCLUSION

A Rotman lens antenna based on SIW technology in center frequency of 16 GHz has been designed in this paper. SIW combines the advantages of lightweight and low cost fabrication of printed circuit and the low loss characteristic of closed structures. This antenna is composed of two parts: Rotman lens and array antenna. In section II a Rotman lens with 7 inputs and 7 outputs has been designed. Also, the design method of SIW has been explained in this section. In section III, an array of Vivaldi antennas has been connected to Rotman lens and the whole structure has been simulated by two full-wave softwares. The results of two simulators have good similarities and show that this kind of Rotman lens antenna has good performance at this frequency band.

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