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Design and Fabrication of Wideband Millimeter-Wave Directional Couplers With Different Coupling Factors Based on Gap Waveguide Technology

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ABSTRACT A class of wideband directional couplers suitable for achieving different coupling levels are proposed in this paper. The proposed couplers have been implemented using the double-layer groove gap waveguide at the millimeter-wave frequency range. They are composed of two parallel groove gap waveguide parts placed on top of each other in such a way that the coupling between the two waveguide sections can be achieved via the coupling structures placed in the common wall. Usually, the coupling layer consists of two rows of holes and depending on the number of holes the coupling levels can be controlled. The manifest and applicable property of the proposed directional coupler is that the coupling level can be simply changed using the different coupling layers without changing the top and bottom groove waveguides and transitions. As another significant advantage of the proposed coupler, there is no requirement of good electrical contact among different metallic parts of the structure, which considerably simplifies the manufacturing processes and mechanical assembly at millimeter-waves applications. For verification purpose, three sample couplers with coupling levels of 10, 20, and 30 dB have been designed, fabricated, and measured. To make the device accessible and measurable using the standard rectangular waveguides, two types of transitions from the groove gap waveguide to standard WR-15 are designed. The simulation and experimental results are in good agreement and show that the proposed couplers have large bandwidth for return loss level of 20 dB, coupling level of 10 ± 1 , 20 ± 1 , and 30 ± 1 dB, and isolation level of 30, 35, and 40 dB over the desired frequency band of 50–70 GHz. The proposed directional couplers can be used as good candidates at millimeter-wave frequencies for probing and the design of compact integrated microwave circuits and systems, such as antenna array feeding networks.

INDEX TERMS Directional coupler, gap waveguide technology, millimeter wave, V-band applications.

I. INTRODUCTION

Directional couplers are passive four-port devices which have different applications such as signal quality and power level, measuring reflections, mixing signals and for isolation of signal sources in microwave and millimeter-wave systems. All of these applications make use of the property that power flowing in one direction in the main branch of the coupler induces a power flow in only one direction in the auxiliary

branch. Power monitoring usually requires a coupling not tighter than 20 dB and a directivity of only moderate value. In reflection measurements, usually a coupling tighter than 20 dB and a directivity greater than 30 dB are desirable.

Many early proposed directional couplers, including Bethe-hole coupler [1], multi-hole coupler [2], and Schwinger coupler [3], were invented and characterized in the 1940s. These components can be implemented in the context of different transmission line structures such as waveguides [4]–[6], microstrips [7], [8], substrate integrated waveguide (SIWs) [9]–[11]. Planar technologies offered

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major advantages over their waveguide counterpart, namely, compactness, planarity, low fabrication cost, and integrability with active microwave components and circuits. However, the dielectric loss in millimeter-wave range hinders the PCB based couplers to be used in many applications. Waveguide directional couplers have the advantages of low loss and high power handling capacity. Despite these advantages, waveguide couplers have limited applications especially in millimeter-wave circuits due to the 3D structure and high manufacturing cost. In Bethe-hole waveguide couplers, the coupling is done by putting a waveguide on top of another one and by making an aperture hole in their common wall electromagnetic signal would be coupled into the other waveguide. This type of coupler is usually narrow band, but to increase the bandwidth a series of holes is made in the common wall of the guide and is called a multi-hole directional coupler [12]–[14]. For many applications, it is desirable that the power division or coupling be constant with frequency in order to reduce measurement errors. However, most design procedures of wideband waveguide directional couplers require different sections that increase the device length.

Over the past few years, the millimeter wave frequency band has got a lot of attention with the evolution of many new wireless applications. In smaller wavelengths, the use of traditional technologies such as hollow metallic waveguides, microstrip lines, and SIWs are more challenging. Although classical waveguide technology is well known for low loss and higher power handling capability, it requires extremely accurate fabrication processes and also a fine assembly approach to ensure good electrical contacts among different metal blocks of the waveguide components. Moreover, the poor integration ability of metallic waveguides with active microwave components limits their usage to a certain extent [15]. Therefore, there is a definite need to develop new technologies that not only maintain the benefits of the existing ones but also resolve their weaknesses. Recently, gap waveguide technology based on the theory of PEC/PMC parallel-plate configuration was proposed in [16] as an innovative technology well suited for millimeter-wave RF applications with promising characteristics and potential to overcome aforementioned challenges. Reviewing the literature revealed that several passive components based on gap waveguide technology have been presented over the past few years, such as high gain and high efficiency planar array antennas [17]–[19], High Q filters [20]–[22], couplers [23], [24] and packaging [25].

A survey of literature on the millimeter-wave couplers indicates that the design of different directional couplers for millimeter-wave applications has been a subject of extensive research. Different kinds of couplers have been designed such as waveguide, microstrip and SIW structures [26]–[31]. This paper presents the investigation and development of innovative groove gap waveguide directional couplers design centered at the 60 GHz for potential next generation communication systems and V-band applications. The coupling

level of directional couplers can be simply changed using the different coupling layers without changing in groove waveguide sections and transitions and there is no requirement of good electrical contact among different metallic parts of the structure even though the waveguide sections has been splitted in the H-plane.

Section II is devoted to the basic idea and details of groove gap waveguide. This is followed by the directional coupler design procedure, in Section III. Design of transitions between groove waveguide to rectangular waveguide is given in Section IV. Section V explains the experimental validation of the final designs. Finally, a comparison table is presented in Section VI to show the performance improvement of the proposed couplers compared to other published work.

II. GROOVE GAP WAVEGUIDE

In gap waveguide technology, the propagation direction of the wave is controlled by using a guiding structure such as ridge, groove or inverted microstrip line [16]. A periodic pin pattern around the guiding structure eliminates any possible leakage and higher order modes. The pin pattern acts as a high impedance surface and prevents electromagnetic waves to propagate and leak in undesired directions within the stop-band. Fig. 1(a) shows the basic layout of the groove gap waveguide. In this structure, there is no requirement for a metallic contact among the layers. The boundary conditions for the field in the groove are the ones given by four metal walls, but with the equivalent of a magnetic conducting strip in each of the corners between the upper horizontal plate and the two vertical metal walls. The number of pin rows around the groove is very important for gap waveguide structures. Based on presented analysis in [16], two rows of pins are appropriate for such structures. In fact, the leaked energy is as low as 45 dB after two rows of pins which is acceptable for many applications.

The dimensions of the groove structure should be selected to achieve a stop-band covering 60-GHz frequency band. The influence of varying pin dimensions in dispersion diagrams of the structure has been studied in detail in [16]. According to these studies, the dimensions are chosen as the following: $h = 1.3$ mm, $a = 0.5$ mm, $g = 0.2$ mm, and $p = 1$ mm. The dispersion diagram is calculated using the Eigen-mode solver of CST Microwave Studio for the unit cell with periodic boundary condition. Fig. 1(b) shows the dispersion diagram of an infinite 2-D pin array. The width of the groove w is selected to be 0.5λ at the lower cutoff of the pin surface (50 GHz), i.e., $w = 3.7$ mm. Observe that the stop-band of the periodic cells starts after 40 GHz and ends around 90 GHz covering the V-band.

III. DIRECTIONAL COUPLERS CONFIGURATION

The structure of the multi-hole directional coupler is shown in Fig. 2. This coupler is made of two parallel groove gap waveguides kept one over the other having a common broad wall. Though the waveguides axis and coupling apertures can be chosen arbitrary, but to simplify the design and fabrication

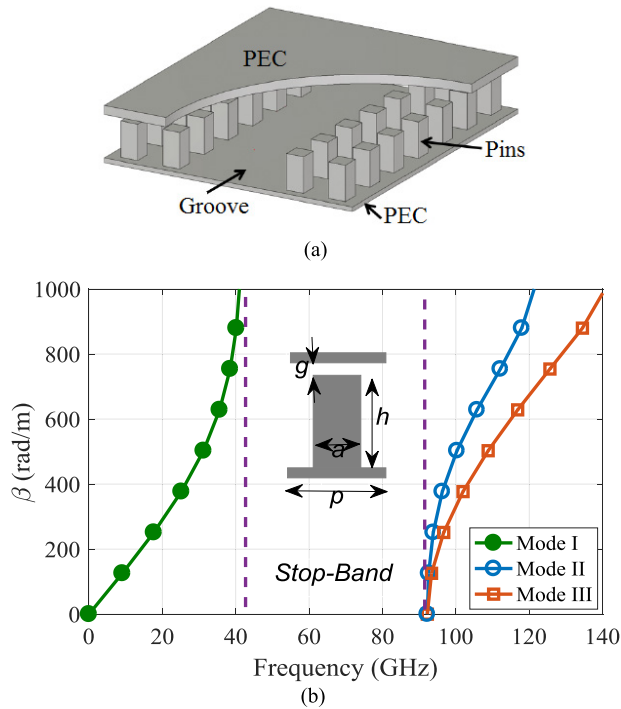


FIGURE 1. (a) Groove gap waveguide structure. (b) Dispersion diagram of the unit cell of the periodic pins ($a = 0.5$ mm, $h = 1.35$ mm, $p = 1$ mm and $g = 0.2$ mm).

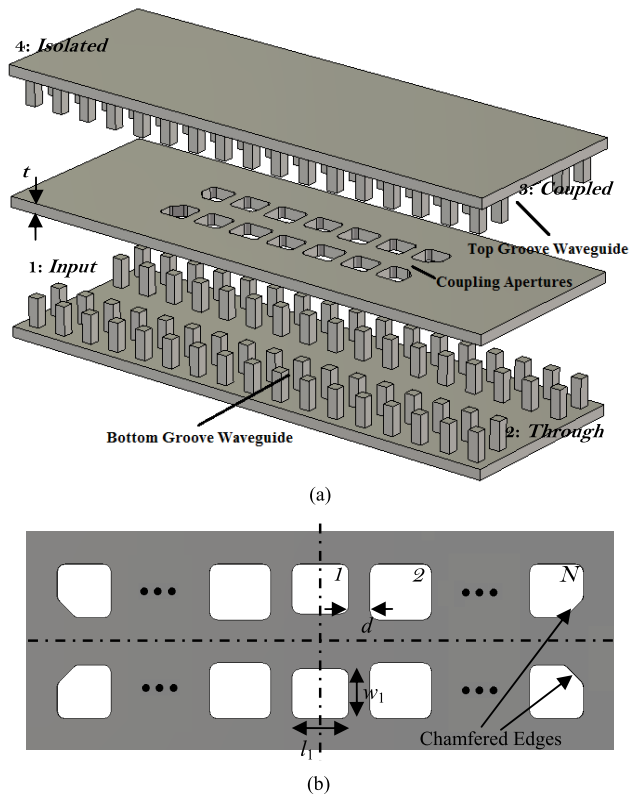


FIGURE 2. (a) Exploded perspective view of groove gap waveguide directional coupler. (b) Coupling apertures.

process, we consider that two groove waveguides are the similar and placed on top of each other. Ports 1, 2, 3, and 4 are

the input, through, coupled, and isolated ports, respectively. The groove waveguides are coupled to each other by some apertures. Referring to Fig. 2, the coupling coefficient (C), directivity (D), and isolation (I) are defined as follows:

$$C = 10 \log_{10} \left| \frac{P_{in}}{P_f} \right| = 20 \log_{10} \left| \frac{1}{S_{31}} \right| \quad (1)$$

$$D = 10 \log_{10} \left| \frac{P_f}{P_b} \right| = 20 \log_{10} \left| \frac{S_{31}}{S_{41}} \right| \quad (2)$$

$$I = 10 \log_{10} \left| \frac{P_{in}}{P_b} \right| = 20 \log_{10} \left| \frac{1}{S_{41}} \right| = C + D \quad (3)$$

where P_{in} is the incident power at the input port, P_f is the coupled power, and P_b is the power output of the isolated port. By increasing the number of coupling apertures, the bandwidth is increased. In the designing procedure for directional couplers, in addition to number of apertures, distances between them, and the apertures dimensions should be determined. As mentioned earlier, the analysis of multi-hole couplers was well studied in the literature.

By using two or three rows of holes in broad wall, the stronger coupling would be obtained. Shelton, Cohn and Levy have studied multi-row couplers and have given the coupling curves in terms of holes diameters for X and Ku bands waveguides [30], [31]. Their research demonstrated that 2-rows is better than 3-rows and for shortening the length it is not possible to use 3-rows holes. Therefore, we use two rows of apertures in the coupling region. To improve the matching in the ports, the side apertures are chamfered with chamfer radius of c . In addition, if the common wall of waveguides has finite thickness and if the frequency is below resonance, any aperture acts as a short-length waveguide and so the attenuation will be increased. The following formula for the added attenuation has been suggested [31]:

$$\alpha_t = \frac{54.6 t A}{\lambda_c} \sqrt{1 - \left(\frac{\lambda_c}{\lambda} \right)^2} \quad (4)$$

wherein t , λ_c and A are the wall-thickness, cutoff wavelength of the waveguide and additional factor, respectively. Additional factor is a function of the thickness t and in the case of a circular aperture appears to be only slightly greater than one. For very large thickness, the increase in attenuation will approach asymptotically the attenuation of the principal mode in a waveguide whose cross section is the shape and size of the aperture, and whose length is equal to the thickness of the wall. On the other hand, from the practical point of view, using a thin wall may led to some problems in fabrication and assembling process, which may affect the coupler performance. To overcome this problem, the thickness of metal plate is chosen 1 mm and then the design process is continued.

According to [30], with three sets of double-hole apertures and wall thickness of 1 mm, a coupler with coupling value approximately 30 dB can be achieved. Here, optimization in CST MWS finds the desired dimensions of the apertures due

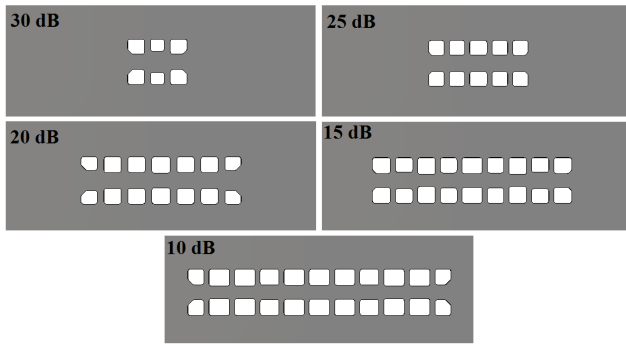


FIGURE 3. Three, five, seven, nine and eleven sets of double-hole apertures in common brad wall of two groove gap waveguides.

TABLE 1. Design parameters of directional couplers.

Coupling Aperture	30 dB (mm)	25 dB (mm)	20 dB (mm)	15 dB (mm)	10 dB (mm)
1	$l_1 = 1.12$ $w_1 = 1.00$	$l_1 = 1.40$ $w_1 = 1.20$	$l_1 = 1.47$ $w_1 = 1.21$	$l_1 = 1.64$ $w_1 = 1.29$	$l_1 = 1.66$ $w_1 = 1.36$
2	$l_2 = 1.36$ $w_2 = 1.23$	$l_2 = 1.25$ $w_2 = 1.20$	$l_2 = 1.50$ $w_2 = 1.21$	$l_2 = 1.35$ $w_2 = 1.24$	$l_2 = 1.65$ $w_2 = 1.32$
3	$d = 0.5$ $c = 0.4$	$l_3 = 1.25$ $w_3 = 1.21$	$l_3 = 1.28$ $w_3 = 1.27$	$l_3 = 1.43$ $w_3 = 1.37$	$l_3 = 1.59$ $w_3 = 1.30$
4		$d = 0.4$ $c = 0.3$	$l_4 = 1.09$ $w_4 = 1.28$	$l_4 = 1.41$ $w_4 = 1.19$	$l_4 = 1.65$ $w_4 = 1.32$
5			$l_5 = 1.47$ $w_5 = 1.29$	$l_5 = 1.61$ $w_5 = 1.27$	
6		$d = 0.5$ $c = 0.45$	$d = 0.4$ $c = 0.3$	$l_6 = 1.33$ $w_6 = 1.31$	$d = 0.4$ $c = 0.3$
					$d = 0.4$ $c = 0.3$

to a suitable fitness function which is defined as

$$Fitness = \left(\frac{1}{M} \sum_{m=1}^M (|S_{11}(f_m)|^2 + |C - S_{31}(f_m)|^2) \right)^{0.5} \quad (5)$$

where $S_{ij}(f_m)$ are scattering parameter of the directional coupler at frequency sample f_m , C is the desired coupling coefficient and M is the number of sample frequencies in the desired frequency range from 50 to 75 GHz.

Optimized values of design parameters of directional couplers with three, five, seven, nine and eleven sets of double-hole apertures are given in Table 1. The simulated results are shown in Fig. 4. The simulated S_{11} - and S_{41} -magnitude of couplers are below -20 dB and -30 dB, respectively from 50 to 75 GHz. Through optimization, it was found that the compromise must be made between good coupling flatness and high directivity. Observe that the excellent return loss, good coupling flatness and broadband performance are achieved for these structures and the coupling value can be changed only by changing the number of apertures. This adds the possibility of reconfiguring the coupler performance without manufacturing completely new geometry. The reconfigurability could be obtained only by changing the metal plate with the coupling apertures.

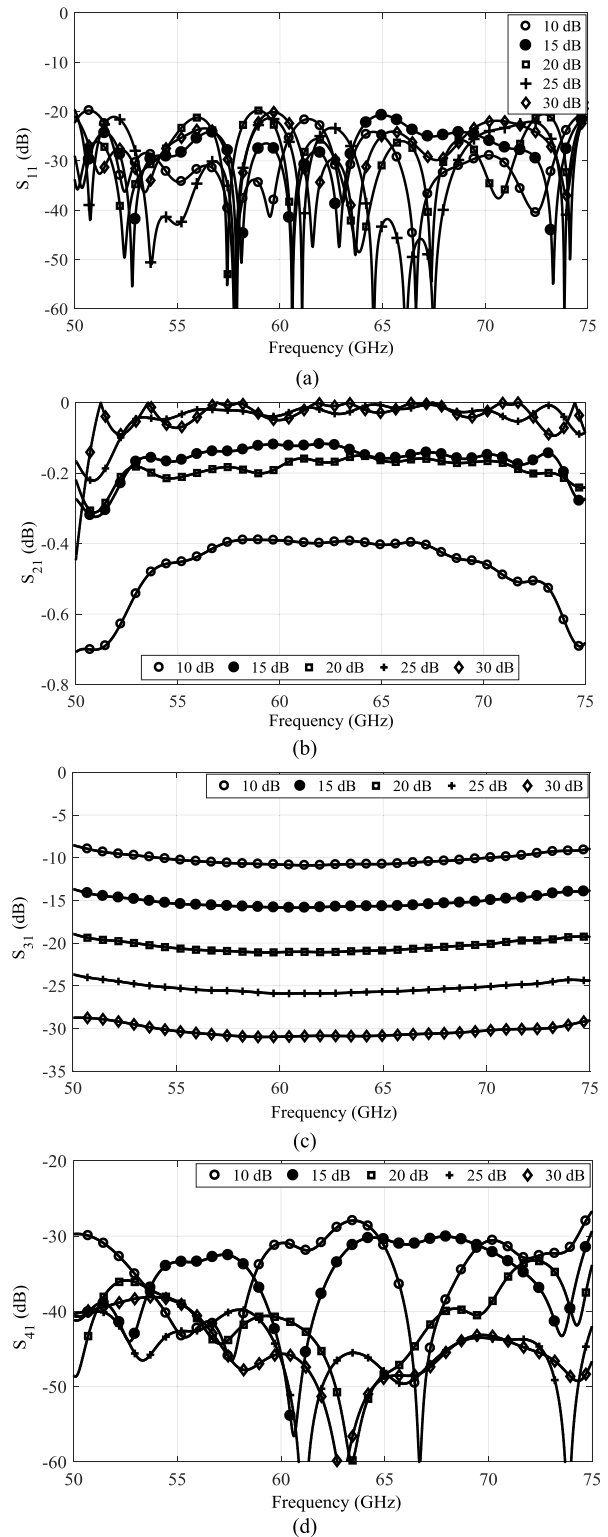


FIGURE 4. S-Parameters of designed directional couplers with coupling factor of 10, 15, 20, 25 and 30 dB.

IV. DESIGN OF TRANSITION

To make the directional coupler accessible and measurable by a network analyzer, transitions between groove gap

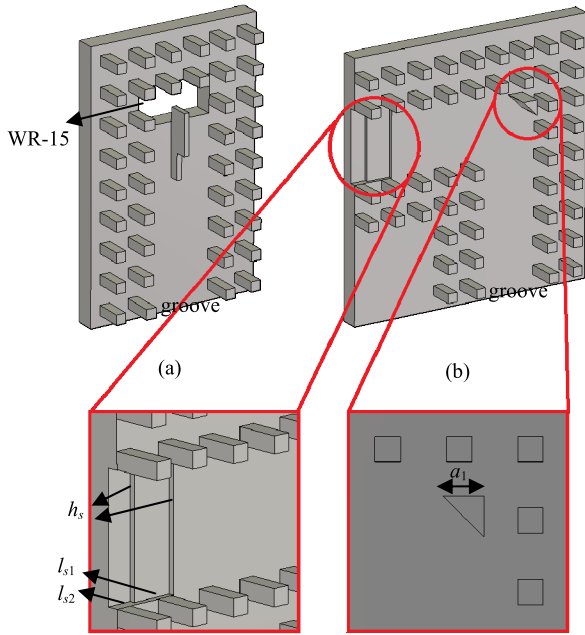


FIGURE 5. Two proposed transition from groove gap waveguide to standard WR-15. (a) Transition 1. (b) Transition 2. The top metal plate is not shown. The optimized values of length and height of step in transition 1 are 1.32 mm and 0.61 mm. The optimized values of transition 2 are $h_s = 0.18$ mm, $l_{s1} = 1.14$, $l_{s2} = 2.77$ mm and $a_1 = 0.88$ mm.

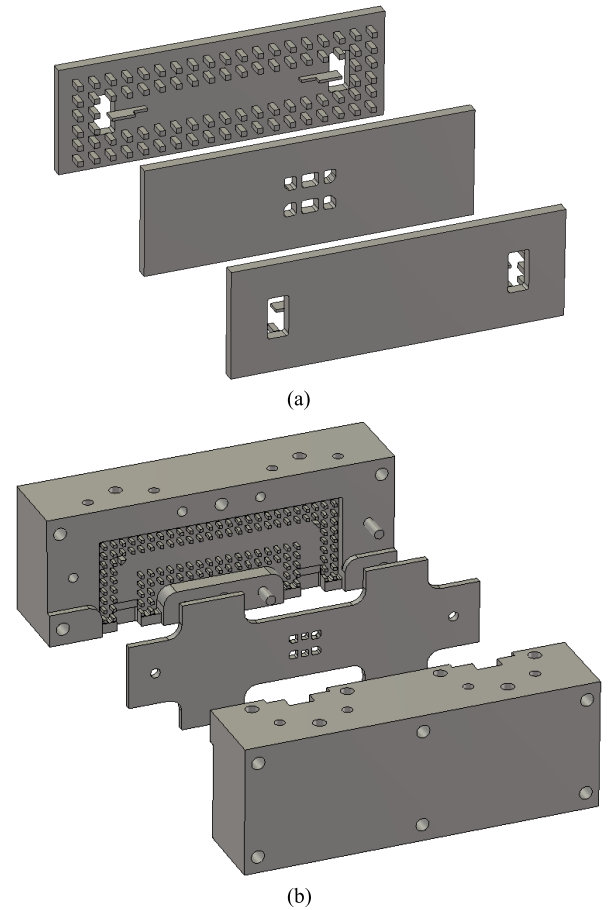


FIGURE 7. Configuration of coupler structure with (a) transition 1 and (b) transition 2.

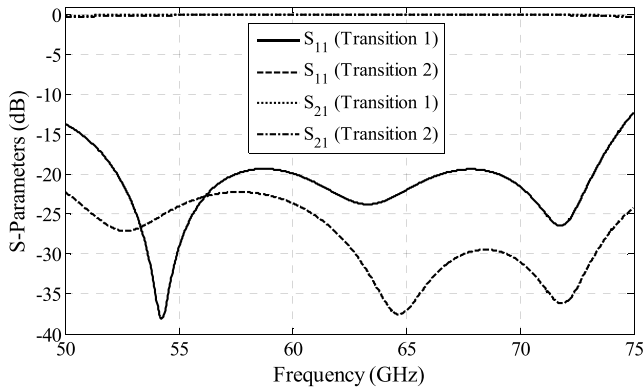


FIGURE 6. S-Parameters of two proposed transitions from groove gap waveguide to WR-15.

waveguide and rectangular waveguide should be designed. Here, we introduce two wideband gap waveguide transitions to standard WR-15 rectangular waveguide operating in the 60-GHz band. The overall topologies of these transitions are shown in Fig. 5.

As shown in Fig. 5(a), a simple transition is designed to match the TE₁₀ mode of the ridge gap waveguide to the TE₁₀ mode of standard WR-15. A metal brick section with a step is placed on the bottom wall of the groove with an extension to the waveguide opening. For achieving the desired matching, all the parameters of the structure are optimized. The simulation results are shown in Fig. 6. Observe that a -15 dB return loss with an insertion loss better than 0.1 dB is achieved between 50-75 GHz.

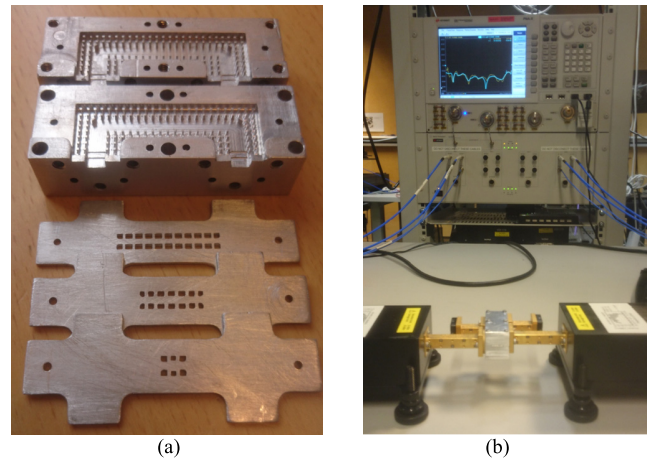


FIGURE 8. (a) Photograph of fabricated 10-, 20- and 30-dB directional couplers. (b) Directional coupler under test.

In the second transition as depicted in Fig. 5(b), four 90° bends are added to the coupler to make the measurement and application more convenient. In the proposed bend structure, two grooves are connected using an H-plane cross bend. By moving the position of tuning pin in the bend, low reflec-

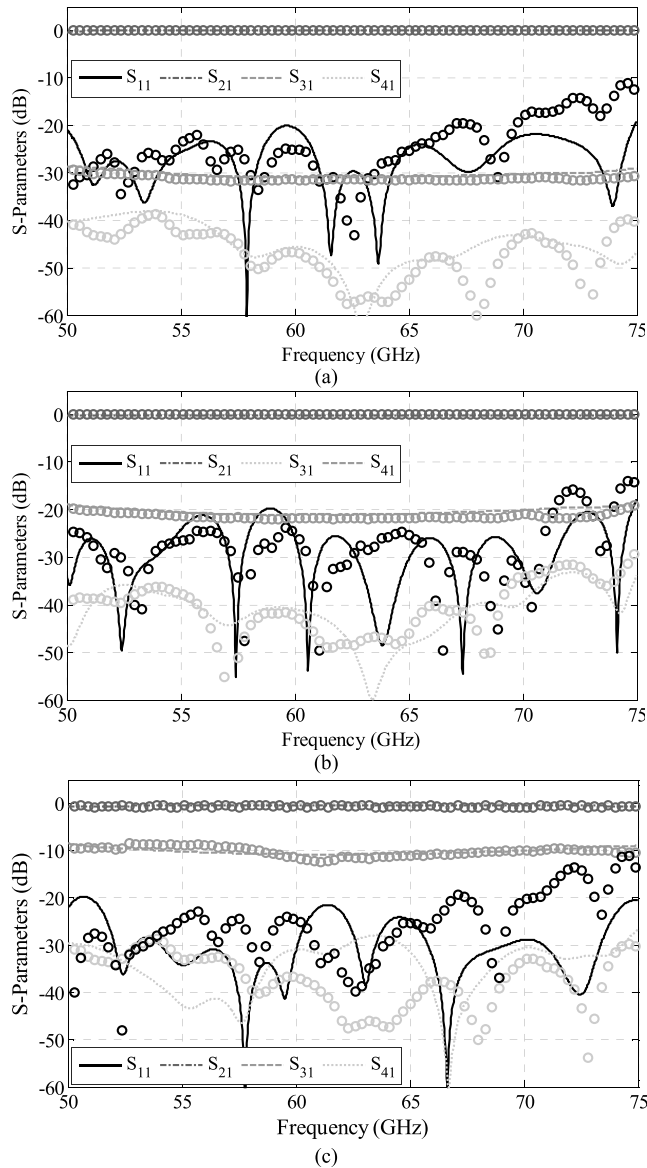


FIGURE 9. Simulated and measured S-Parameters of fabricated 30-, 20- and 10-dB directional couplers. Measured values are shown with circles.

tion coefficient can be achieved over the desired frequency band. In addition, due to a height difference between standard WR-15 and groove waveguide, a two sections step is implemented in the bottom plate of the gap waveguide. The simulation results show a 24-dB return loss with an insertion loss better than 0.1 dB is achieved between 52-68 GHz as shown in Fig. 6.

Fig. 7 shows the geometric configuration of the proposed directional coupler with transitions. In the configuration with the first transition, achieving a good matching in the ports requires a very thin metal brick (mention the thickness of that ridge section) that is challenging from practical point of view and may be broken in the fabrication process. Due to this reason, the coupler with the second transition is fabricated and measured. In this design, the bottom and top layers are

TABLE 2. Comparison with some other reported couplers.

Technology	Freq. (GHz)	B.W (%)	Coupling (dB)	Isolation (dB)	Dimensions (cm)
SIW [11]	28 - 38	30.3	20 ± 1	≥ 30	5×3×3
SIW [26]	12.4 - 18	36.8	20.5 ± 1	≥ 30	10×10×3
Circular Waveguide [27]	19 - 26	31.1	26 ± 4	≥ 40	10×5×5
Rectangular Waveguide [28]	85 - 96	12	3.3 ± 0.6	≥ 20	5×5×1
Rectangular Waveguide [29]	55 - 68	21	28 ± 2	≥ 20	7×4×4
Commercial Coupler [32] (SMW15HC001)	50 - 75	40	10 ± 1.5	≥ 30	9×2.5×2
This Work	50 - 70	33.3	10 ± 1	≥ 30	4.9×2.4×2
	50 - 72	35.5	21 ± 1	≥ 35	
	50 - 70	33.3	31 ± 1	≥ 40	

kept the same which reduces the complexity and cost of fabrication.

V. FABRICATION AND MEASUREMENT

There are different fabrication techniques that will suit planar surfaces with such periodic pin texture, such as Computer Numerical Control (CNC) machining, die-sink Electric Discharge Machining (EDM), Direct Metal Laser Sintering (DMLS) 3D printing. All these suggest that flexible manufacturing methods within affordable cost can be used to fabricate the designed couplers. Here, to verify the proposed design, prototypes of directional couplers with 10 dB, 20 dB, and 30 dB coupling level are fabricated by using CNC metal milling machining in Aluminum. The photograph of the fabricated prototype with total size of 49×24×20 mm³ is shown in Fig. 8(a). Figure 8(b) shows a photograph of the measurement setup of the proposed directional couplers. The measurement is performed by using a Keysight PNA N5242A and V-band extender modules. The simulated and measured S-parameters of the couplers are depicted in Fig. 9. Observe that the measured reflection coefficient is below -20 dB over the 50 GHz to 70 GHz frequency range for three couplers and below -10 dB up to 75 GHz. The transmission coefficients between ports #1 and #3 are 10 ± 1 dB, 21 ± 1 dB and 31 ± 1 dB, respectively over the same frequency range. The transmission loss is principally attributed to the conductor loss. The measured isolations between port #1 and port #4 of couplers are better than 30, 35 and dB, respectively in the whole bandwidth. The discrepancy between simulated and measured results is due to the loss of electromagnetic energy, the fabrication inaccuracies and assembling tolerances, but the measured and simulated results still agree well with each other.

To evaluate the proposed design, Table 2 compares the specifications of proposed coupler with some previously published coupler works. This broadband waveguide directional coupler with good coupling flatness and excellent return loss

can be used as good candidates at different millimeter-wave frequencies.

VI. CONCLUSIONS

Directional couplers with different coupling coefficients have been proposed based on gap waveguide technology, which has good coupling flatness and high directivity over the V-band. The main advantage of gap waveguide based coupler is that it does not require good electrical contact among different metallic parts of the multi-layer waveguide blocks which simplifies the mechanical assembly processes for millimeter-wave components. As an example, a prototype coupler has been designed, fabricated and measured. Measured results from the couplers shows that the directivity is higher than 30 dB and the coupling coefficient can be easily chosen as 10, 20 and 30 dB, etc. The prototypes are easily designed, and can be fabricated at low cost with many conventional fabrication techniques. The results are valuable for the design and evaluation of broadband microwave components at millimeter-wave frequencies.

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