High Q Power Divider/Combiner with High Output Isolation using Substrate Integrated Waveguide Technology

***Abstract*- A power divider (PD)/ power combiner (PC) with high quality factor and enhanced output ports isolation using substrate integrated waveguide (SIW) technology is proposed. An SIW cavity is designed to provide a high quality factor filtering response and an SMD resistor is attached between two output ports to realize the high isolation. The value of the applied resistor is calculated by using the even and odd mode analysis. The measured results obtained from testable model are in good agreement with the simulated results. These results show that the return loss is 23 dB, the minimum insertion loss is 4.55 dB including intrinsic 3 dB insertion loss of PD, and the isolation between output ports is 20 dB, which shows that the proposed design could be an important component in microwave circuits.**

***Index Terms*-** Cavity resonator, power combiner, power divider, Q-factor, substrate integrated waveguide (SIW).

I. INTRODUCTION

The rectangular metallic waveguide PD has the benefits of the low loss, high quality factor, and high selectivity [1], but their high cost, bulky volume, and lack of integration with planar circuits put some serious limitations on the design and applications of the rectangular waveguide PD [2], [3]. Recently, substrate integrated waveguide (SIW) structure is introduced. The SIW structure consists of two rows of metallic vias placed in an alternating way in a substrate. The metal walls up and down of the substrate with alternating walls on either side, which have a similar role with the walls of a rectangular waveguide [4]. The SIW structure has the advantage of the conventional waveguide and is compatible with planar circuits [5].

The microstrip PDs such as Wilkinson PDs have a good performance in terms of isolation, return loss, and insertion loss [3], [6]. However, in high frequency applications, they will have a very small size and their fabrication will be much more difficult [7]. Also, the variation in the results may be introduced by the coupling between the output ports. Furthermore, due to the large bandwidth, Wilkinson microstrip PDs do not enjoy high quality factor.

The SIW structure, which contains two rows of metallic vias on both sides of the substrate, has

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been made a drastic change in the design of the microwave circuits because of its high compatibility with planar circuits, low cost, compact size, high quality factor, and etc. [8].

The design procedure of Wilkinson microstrip PD has been used to design the SIW PDs [9-12]. The introduced PDs have the advantages such as proper dimensions for fabricating in high frequencies and higher quality factor in comparison with Wilkinson microstrip PD. However, the problem of designing a PD with high quality factor, suitable isolation, and good frequency selectivity which has applications like oscillators, power amplifiers, and antenna power supply still exists.

Cavities are one type of SIW structures with all sides connected to ground. Therefore, the structure has found a resonant mode which leads to high quality factor and make it convenient for filtering application [13], [14]. The main idea of this paper is to design a PD using SIW cavities in order to achieve a high quality factor and appropriate frequency selectivity and also create proper isolation in output ports using an SMD resistor.

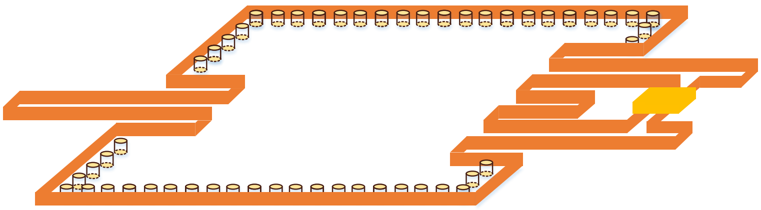
In [9-11], several power dividers based on substrate integrated waveguide by improving isolation performance have been designed. In these power dividers, the power is split after the isolation resistor which is against the standard Wilkinson topology [12]. In [12], a compact ring shaped PD has been proposed. However, this kind of power divider has not the suitable filtering response. Also in [9], [11], [12], the slot in the middle of the circuit can be cause radiation. In [15], a PD with arbitrary power dividing ratio is presented. This design has the disadvantage of the isolation among output ports. In [16] an ultra-wideband PD using SIW has been proposed. This PD has good bandwidth and compact size, but has the disadvantage of the isolation among output ports and cannot be used for combining applications. In these structures, while the circuits operate in high frequencies, their dimensions are so big (as shown in Table II).

In the designed PD in this paper, the power is split in the cavity so we have a good filtering response. The isolation is suitable and the size of PD compared to the operating frequency is compact. The designed PD structure is simulated by 3D electromagnetic simulator and then fabricated on a Rogers RO4003C substrate. The simulated and measured results are in a good agreements.

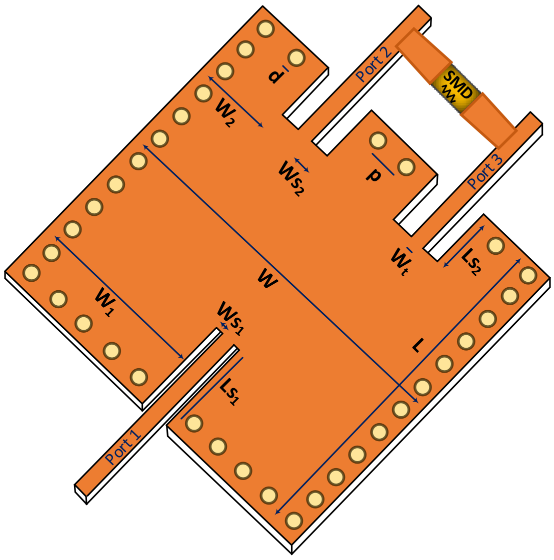
II. DESIGN PROCEDURE

The geometry of the designed PD is shown in Fig. 1. This design procedure can be done in such a way to operate in all millimeter-wave frequencies. The design approach has three steps.

The first is to determine the dimensions of the cavity by using the selected substrate characteristics and the desired resonance frequency. The relations (1), (2), and (3) are used to give a good approximation for the cavity resonance frequency [4], [17].



(a)



(b)

Fig. 1. Configuration of the proposed PD (a) right view (b) solid view.

$$f_{TE_{101}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{L_{eff}}\right)^2} \quad (1)$$

$$W_{eff} = w - \frac{d^2}{0.95p} \quad (2)$$

$$L_{eff} = L - \frac{d^2}{0.95p} \quad (3)$$

Where for the dominant mode of TE_{101}, W_{eff} and L_{eff} are the equivalent width and length of the SIW structure. W and L are the width and length of the SIW, d is the diameter of the vias and p is the distance between two adjacent vias. μ_r and ε_r refer to the relative permeability and permittivity of the substrate respectively and c is the velocity of light in the free space.

The second step is to determine the location of the input and output ports. As shown in Fig. 2, the electric field in the middle of each cavity side reaches its maximum, which is higher than the other places in the cavity. Therefore, these places are the best areas to implement the input and output ports.

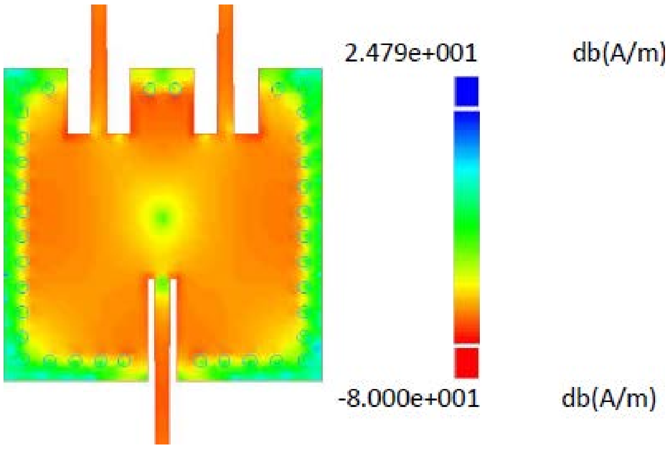


Fig. 2. Magnitude of the surface current on the cavity.

The center coupling enjoys a better quality factor compared with the quadrature coupling or double coupling [18]. The existing symmetry in Fig. 1 is for the purpose of equal power division between the two output ports.

The final step is to make the isolation between the output ports which is done by placing an SMD resistor out of the cavity and close to the output ports as can be seen in Fig. 1. The even and odd mode techniques are used to obtain the resistor value. The return loss of the output ports and isolation between output ports of a symmetric three-port network can be calculated by the even and odd modes scattering parameters as follows [19]:

$$S_{22} = S_{33} = \frac{S_{22}^{e} + S_{22}^{o}}{2} \tag{4}$$

$$S_{23} = \frac{S_{22}^{e} - S_{22}^{o}}{2} \tag{5}$$

In this circuit, without the resistor, the scattering parameter of S_{22} is suitable and equal to zero in the even mode. But, in the odd mode, the SIW cavity is not excited and the scattering parameter of S_{22} is not proper. A resistor is used to improve the operation of the circuit in the odd mode. The equivalent circuit of the proposed PD in the odd mode is illustrated in Fig. 3. In this mode, the SIW cavity is not excited and it is open circuit. From (6) it can be seen that to obtain $S_{22}^{o} = 0$, the load impedance Z_{in} must be equal to the characteristic impedance of the port 2. Then the resistor value can be calculated from (7) [19].

$$S_{22}^{o} = \frac{Z_{in} - Z_{0}}{Z_{in} + Z_{0}} \tag{6}$$

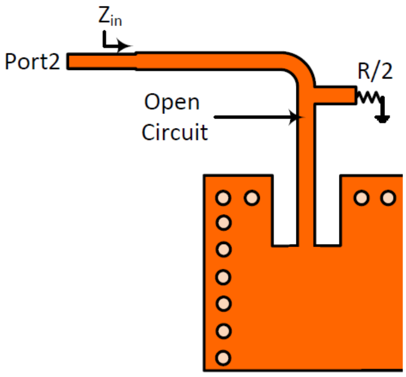


Fig. 3. Equivalent circuit of the proposed PD in the odd mode.

Table I. Dimensions of the proposed SIW PD

Parameters	**Value (mm)**
W	22.86
W_1	10.28
W_2	3.80
W_{s1}	0.508
W_{s2}	1.9
Wt	1.27
L	22.86
L_{s1}	7
L_{s2}	4.03
d	0.63
p	2.03

$$Z_{in} = Z_{0t}\frac{\frac{R}{2} + jZ_{0t}\tan\theta}{Z_{0t} + j\frac{R}{2}\tan\theta} \qquad (7)$$

The resistor value obtaining by (7) is 47 Ω. To validate the presented analytical approach, the proposed PD are simulated with different resistor values. Fig. 4 and Fig. 5 show the simulated amplitudes of S_{22} and S_{23} for different values of resistor and this is explicit that 47 Ω is the best choice for the operating frequency and sizes available because the amplitude of S_{22} and S_{23} are nearly together. Also in the high power applications, to prevent heat dissipation that comes from SMD resistor, a combination of several small resistors in a series format for achieving the required resistor value could be used.

In this circuit, there is no slot and therefore the radiation leakage does not exist. The space between the output ports should be enough to implement the SMD resistor. The parameters of W_{s1}, L_{s1}, W_{s2},

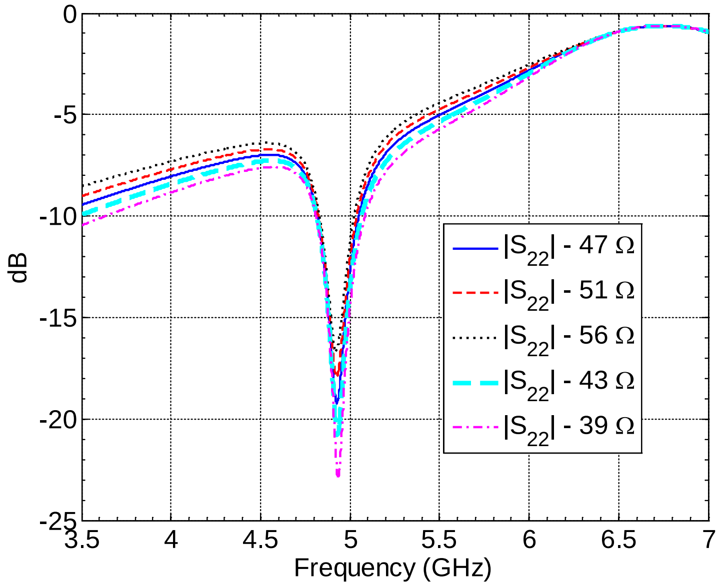


Fig. 4. Simulated $|S_{22}|$ for different values of resistor.

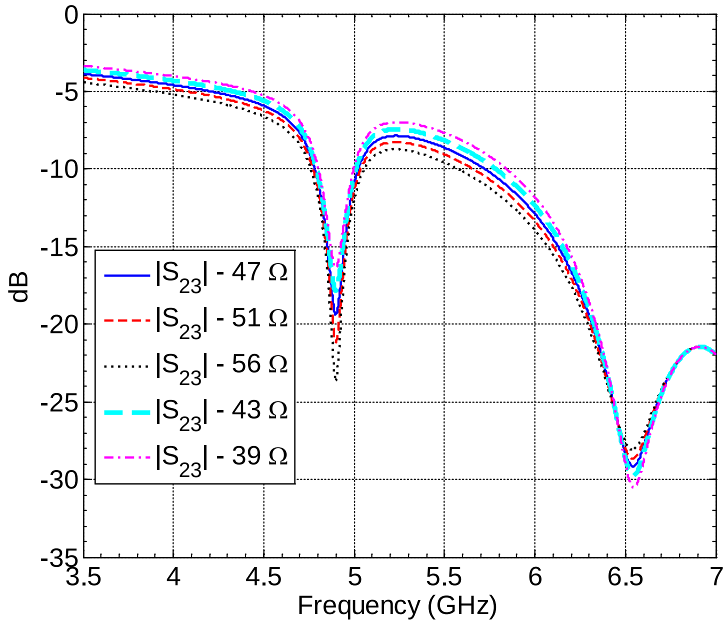


Fig. 5. Simulated $|S_{23}|$ for different values of resistor.

and Ls2 have important roles in optimizing and achieving a better return loss. The width of the 50 Ω microstrip lines are designed to draw out the input and output ports. The values of these parameters are shown in Table I.

III. EXPERIMENTAL RESULTS

To ensure the proposed idea, an experimental model of the designed circuit is fabricated to excite the TE_{101} mode at the center frequency of 4.9 GHz, as illustrated in Fig. 6. A RO4003C (ε_r =3.55,

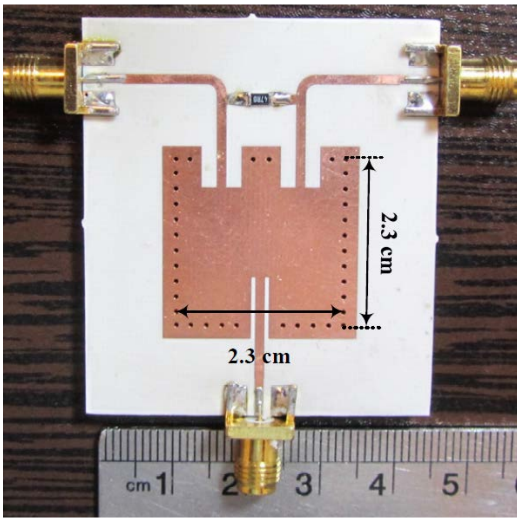


Fig. 6. Photograph of fabricated power divider.

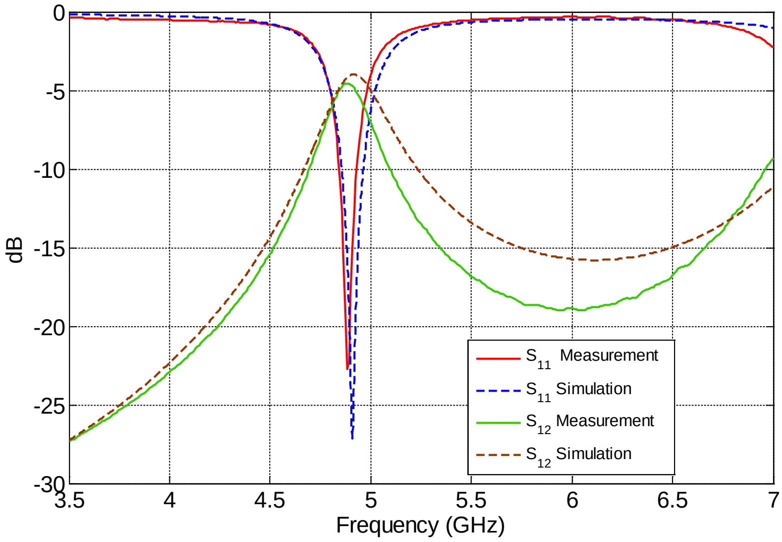


Fig. 7. Return loss ($|S_{11}|$) and insertion loss ($|S_{12}|=|S_{13}|$).

$\tan\delta = 0.0027$) with a thickness of 0.508 mm is used as substrate. The measurement is done by the network analyzer (Rohde & Schwarz, ZVK). The simulated and measured results are shown in Fig. 7 and Fig. 8. A good agreement between the simulated and measured results is obtained. The measured amplitude of S_{11} at the frequency of 4.9 GHz is -23 dB and the measured amplitude of S_{12} is -4.55 dB including intrinsic 3 dB insertion loss of PD. The simulated amplitude of S_{11} and S_{12} are about 4 and 0.45 dB better than the measured amplitude of S_{11} and S_{12}, respectively. As it is clear from Fig. 8, the measured amplitudes of S_{22} and S_{23} at 4.9 GHz are equal to -16 dB and -20 dB, respectively. Basically, they are in agreement with the simulated results and compared with [9-12], [15-16] are in good conditions. The fabrication tolerance, measurement errors, and insertion loss of SMA connectors are the reasons of the differences between the simulated and measured results. The rejection is above -10 dB for the upper stop-band (5.1-6.95 GHz) and shows the high selectivity for the proposed PD.

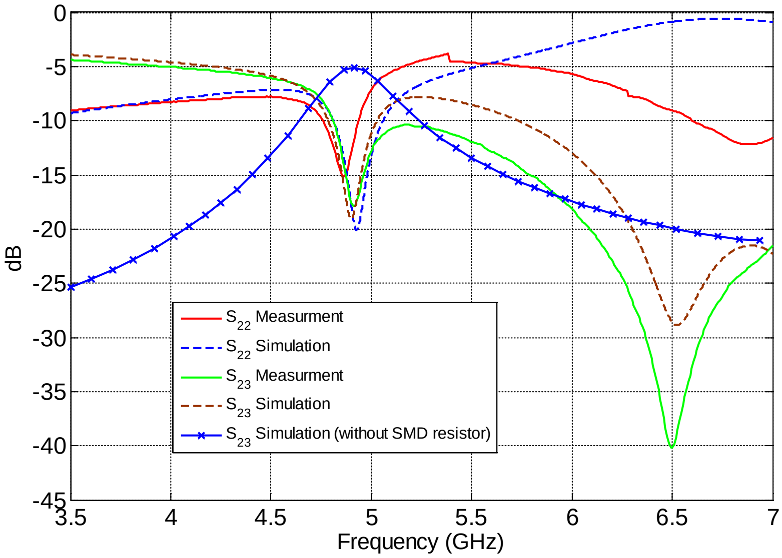


Fig. 8. Output ($|S_{22}|=|S_{33}|$) matching and isolation ($|S_{23}|$).

Table II. Comparison between this work and other works

Reference	Center Frequency (GHz)	Fractional Bandwidth (%)	Dimensions (λ_g^2)	Insertion Loss (dB)	Isolation (dB)
[9]	15	17	3.91×1.64	1.5	<-12.5
[10]	10.5	40	0.75×0.57	1.1	<-10
[11]	11.8	26	2.26×4.15	2.7	<-12.5
[12]	10	25	1.5×0.95	1.2	<-10
[15]	6	60	6.29×3.63	-	-
[16]	92.5	27	3.07×1.76	-	-
This work	4.9	1.59	0.70×0.95	1.55	<-12.5

It is clear from Fig. 7 that S_{11} enjoys a fast inclination and is below -15 dB for a bandwidth of 44MHz. The relations (8) and (9) are used to calculate the loaded and unloaded quality factor [18].

$$Q_l = \frac{f_0}{\Delta f} \tag{8}$$

$$Q_u = \frac{Q_l}{1-|S_{21}|} \tag{9}$$

From these relations, the values of the loaded and unloaded Q factor of the introduced structure are equal to 111 and 272, respectively. Therefore, the quality factor of the proposed structure has a more favorable condition compared with the other PD structures fabricated using SIW technology [9-12].

The performance of this work are compared with other works in Table II. From this Table, this is obvious that the proposed structure in this paper has more compact size than the others while it works in lower frequency and also its isolations is much better.

IV. CONCLUSION

A novel PD/PC based on SIW has been proposed. This design has been centered at 4.9 GHz with the return loss of 23 dB, the minimum insertion loss of 1.55 dB, and output ports isolation of 20 dB. In this design, the isolation between output ports has been achieved by a resistor which the value of this resistor has been obtained by using the even and odd mode analysis. The proposed structure has the advantages of the compact size, low manufacturing cost and easy integration with planar circuits. Also, it can be seen that, a high quality factor, high isolation and high selectivity are achieved. This circuit can be widely used in microwave and millimeter-wave systems (for example 4.9 GHz public safety spectrum).

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