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Design of a Compact 4-Way Power Divider Using $1/64^{\text{th}}$ Mode Elliptically Curved SIW Resonators

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Abstract—A novel compact 4-way power divider is presented here, which consists of $1/64^{\text{th}}$ mode elliptically curved substrate integrated waveguide (SIW) resonators and radial transmission lines. A direct coaxial fed circular patch acting as a radial transmission line is connected with four elliptically curved $1/64^{\text{th}}$ mode SIW resonators, and these resonators are then connected to output terminals. An equivalent circuit model is developed to understand its behavior. It is designed to operate at 3.6 GHz covering the frequencies assigned for 5G in sub-6 GHz band. Conventional PCB techniques are used to fabricate the prototype. The measured bandwidth is 2.2 GHz, ranging from 2.5 GHz to 4.7 GHz, for which the return loss is less than -10 dB. Also, the transmission coefficient between input and each output for the above-mentioned frequency band is -6.4 ± 0.5 dB. It has a very compact footprint of $0.32\lambda_g^2$, which is at least 40% smaller than various SIW based state of the art power dividers.

1. INTRODUCTION

With rapid advancements in modern communication systems, the demand for compact and low-cost RF components with high power handling capacity is increasing. Antennas, power dividers, filters, etc., are the fundamental building blocks of an RF front end. At low frequencies, these devices occupy very large area; so a lot of research is being done to miniaturize these devices. But, most of this research work is based on microstrip and coplanar waveguide technologies, which have their limitations regarding the power handling capacity of the devices [1–5]. Whereas, substrate integrated waveguide (SIW) based devices offer low losses, provide more power handling capacity and are easy to be integrated with planar circuits. But, the size of SIW based devices is larger than their microstrip lines, CPW, counterparts [6].

Various techniques have been used to reduce the size of SIW based antennas, filters, power dividers, etc. [7–11]. A half-mode SIW (HMSIW), which occupies half the area of its full mode counterpart, is first introduced in [7] and later used in [8] to design compact SIW power divider. Similarly, quarter-mode SIW (QMSIW) is used to miniaturize the antenna [9]. Also, QMSIW and 1/8th mode SIW (EMSIW) are used in [10, 11] for miniaturization of SIW based devices without affecting the performance. The size of power divider is further reduced by using direct coaxial feeding, thereby eliminating the need for microstrip to SIW transition [13–15]. 4-way and 8-way power dividers utilizing wedge-shaped $1/32^{\text{nd}}$ mode SIW resonator are presented in [15]. It is noted that the wedge-shaped SIW resonators do not utilize the space optimally.

To increase the isolation between output ports, compact multilayer four way power dividers are presented in [19, 20], which utilize slot coupling between output ports and SIW/HMSIW. Similarly, power dividers based on coupling between SIW backed resonating patch and output lines are reported in [21] and [22] to enhance the bandwidth.

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In the presented paper, a compact power divider which utilizes $1/64^{\text{th}}$ mode SIW resonators folded along the curvature of an ellipse is discussed. The elliptical curvature further decreases the foot-print of the power divider, and the curvature introduces additional capacitance to the circuit, which can be controlled by the curvature itself. The power divider is optimized to cover the frequency range allotted for 5G applications.

2. DEVELOPMENT OF POWER DIVIDER

The developmental stages of the proposed SIW resonator are depicted in Fig. 1. The primary stage consists of a circular SIW cavity operating in TM_{010} mode. It is evident from the electric field distribution that there are a number of planes of symmetry (magnetic walls), i.e., A-A', B-B', C-C', etc.. The cavity is divided into two parts along the plane A-A' to obtain an HMSIW, which is further bisected along O-B' and O-C' to obtain QMSIW and EMSIW respectively. A $1/64^{\text{th}}$ mode SIW can be obtained by repeating the similar procedure three more times. As there is always a plane of symmetry, so there will always be a scope for further size reduction of the resonator, limited to fabrication feasibility. It can be seen that bisecting the resonator along the plane of symmetry reduces its size significantly. However, after the quarter-mode, the maximum dimension of the resonator remains the same. In order to reduce this maximum dimension, the $1/64^{\text{th}}$ mode SIW resonator is folded along the elliptical curvature.

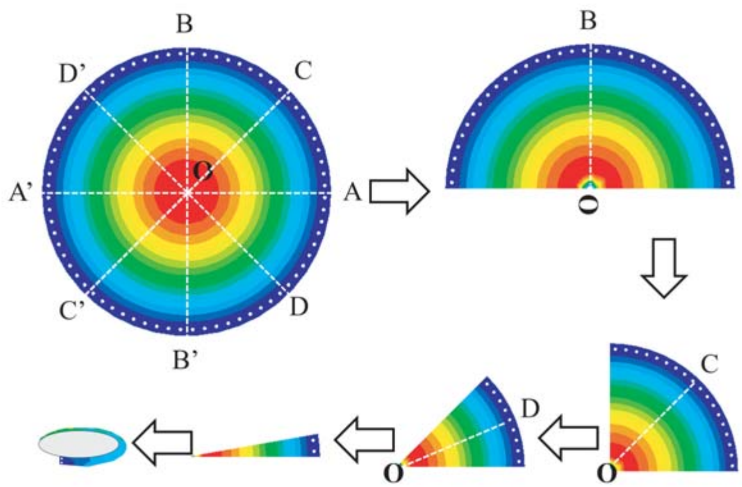

Figure 1. Evolution of elliptically curved SIW resonator.

2.1. Configuration of the Power Divider

The configuration of 4-way power divider is given in Fig. 2, displaying its different views along with the design parameters. A circular slot of radius r_b is etched on the ground, through which feed is provided to the circular patch of radius rd by the coaxial probe having the radius of center pin as r_a. Four SIW resonators operating in $1/64^{\text{th}}$ mode are connected with this patch. All of them are folded along the periphery of an ellipse with major and minor radii of R_a and R_b, respectively. The output ports are connected to these resonators with the help of simple microstrip lines positioned in a way to get the required matching of impedance at between the resonators and the output terminals.

2.2. Equivalent Circuit Model

To get a better understanding, an approximate equivalent circuit is presented in Fig. 3. The cylindrical volume, enclosing the center probe and circular patch, acts as a dielectric-filled radial waveguide, and it can be modeled by a resistive π-network [13, 16, 17]. The formulae for calculation of the shunt and

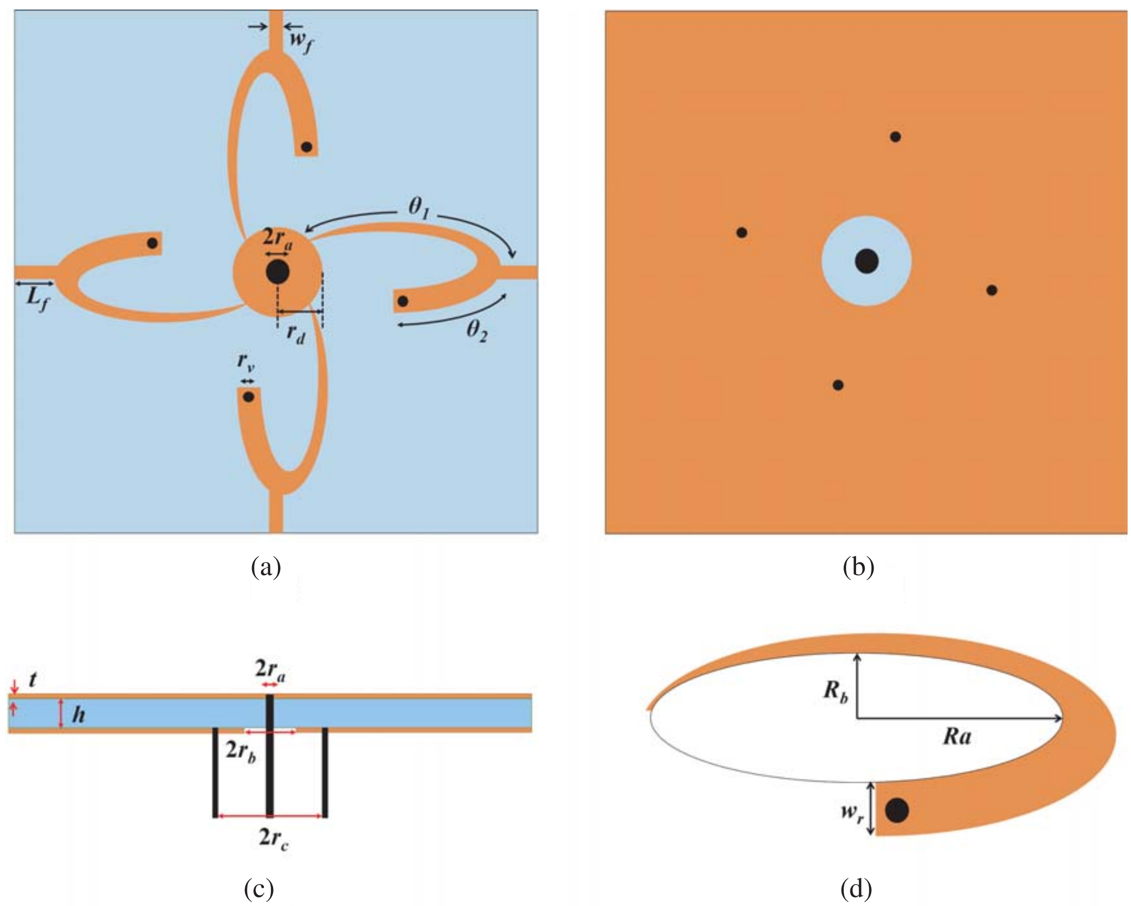

Figure 2. Configuration of the power divider, (a) top layer, (b) bottom layer, (c) cross-section, and (d) detailed view of an elliptical resonator.

series elements of the π-network are given by [16],

$$Y_a = -jY_0(r_b)\left\{ct(x,y)+\sqrt{\frac{y}{x}}cst(x,y)\right\} \tag{1}$$

$$Y_b = -j\sqrt{(Y_0(r_b)Y_0(r_d))}cst(x,y) \tag{2}$$

$$Y_c = -jY_0\left\{-ct(y,x)+\sqrt{\frac{x}{y}}cst(y,x)\right\} \tag{3}$$

where,

$$cst(x,y) = \sqrt{((1+ct(x,y)Ct(x,y))/\zeta(x,y)} \tag{4}$$

$$ct(x,y) = (J_1N_{00}-N_1J_{00})/(J_0N_{00}-N_0J_{00}) \tag{5}$$

$$Ct(x,y) = (J_{10}N_0-N_{10}J_0)/(J_1N_{10}-N_1J_{10}) \tag{6}$$

$$\zeta(x,y) = (J_0N_{00}-N_0J_{00})/(J_1N_{10}-N_1J_{10}) \tag{7}$$

and $J_0 = J_0(kr_b)$, $J_{00} = J_0(kr_d)$, $J_{10} = J_0(kr_d)$, $N_0 = N_0(kr_b)$, $N_{00} = N(kr_d)$, $N_{10} = N(kr_d)$, $x = kr_b$, $y = kr_b$, $k = 2\pi/\lambda$. J and N are the Bessel function and Neuman function, respectively. $Y_0(r_b)$ and $Y_0(r_d)$ are the transmission line admittance of a radial transmission line calculated at r_b and r_d. Each elliptically folded $1/64^{\text{th}}$ mode SIW resonator can be simplified as a tapered transmission line of length R and a maximum width of $2\pi R/64$, where R is the radius of circular SIW cavity at the fundamental resonant frequency (f_0). The output ports are considered as resistive loads of $50\,\Omega$ each and are placed

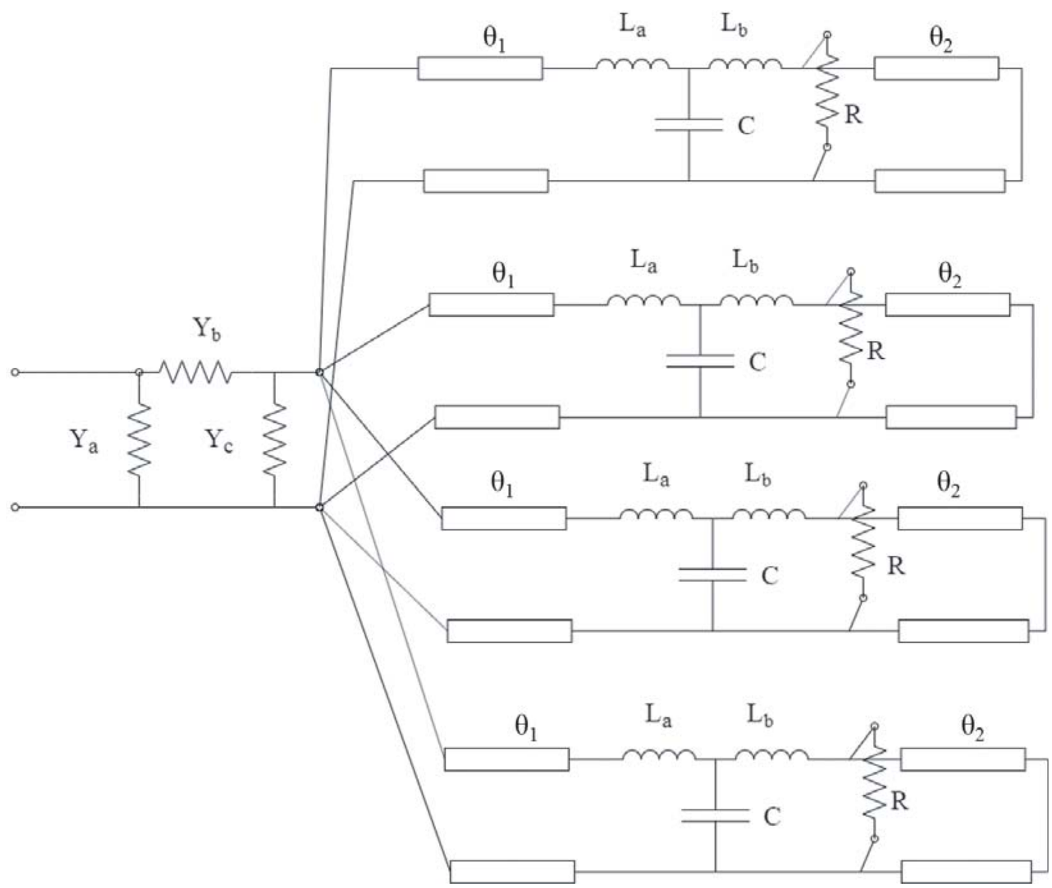

Figure 3. Equivalent circuit model of 4-way power divider.

between two tapered lines of length θ_1 and θ_2. The effect of the curvature of resonators is represented as a T-network consisting of two series inductors and a shunt capacitor [17], placed near load resistances.

From the equivalent circuit, it is evident that the additional passive elements L_a, L_b, and C, which are introduced by the curvature of the resonator, may play a significant role in controlling the bandwidth of the power divider. Therefore, one can control the bandwidth by controlling the curvature of resonator, and the impedance matching can be controlled by the position of output ports, tapering of the resonator, and the patch radius.

3. FABRICATION AND MEASUREMENT

Based on the discussion in the previous section, a 4-way power divider is designed to operate at 3.6 GHz. Ansys HFSS is used to simulate the power divider whereas Keysights' DS is used to simulate the corresponding equivalent circuit model. A low-cost epoxy FR-4 with a thickness of 1.524 mm and the dielectric constant of 4.4 is used as the substrate.

The radius of the circular cavity for TM_{010} mode is calculated by [18],

$$R = 2.405c/\left(2\pi f_0\sqrt{\epsilon_r}\right) \tag{8}$$

where, f_0 is 3.6 GHz. The maximum width of the resonator (w) is kept constant at $2\pi R/64$. The remaining design parameters of the power divider are optimized to minimize the return loss, and equal power is delivered to output ports in the frequency range from 2.4 GHz to 4.8 GHz.

The optimized values of the physical dimensions as well as the extracted values of lumped elements in the equivalent circuit are given in Table 1.

Table 1. Optimized design parameters

Parameter	Value	Parameter	Value
t	0.035 mm	h	1.524 mm
r_v	0.3 mm	r_a	0.45 mm
r_b	1.5 mm	r_c	1.4 mm
r_d	2.25 mm	w_r	1.5 mm
R_a	5.1 mm	R_b	1.8 mm
W_f	2.9 mm	L_f	8 mm
θ_1	8.5 mm	θ_2	6.8 mm
R_a	163 Ω	R_b	0.52 Ω
R_c	512 Ω	C	440 fF
L_a	420 pH	L_b	715 pH

A prototype is fabricated using a simple PCB technique, and its photograph is shown in Fig. 4. The S-parameters are measured using Keysight Technologies' RF Analyzer N9914A. The return loss, transmission coefficient, and isolation parameters of the prototype are measured and compared with the simulated results of the design and its equivalent circuit model as obtained from HFSS and ADS.

The isolation between output ports and the return loss at the input is displayed in Fig. 5, which shows that the measured return loss bandwidth is slightly less than the simulated one. Also, the isolation between two output terminals comes out to be better than −13 dB across the entire frequency range of interest.

Figure 6 shows the transmission coefficient between input and output terminals. It can be observed that the simulated values of transmission coefficients between input and outputs, i.e., S_{21}, S_{31}, S_{41}, and S_{51} are identical, whereas, the measured values vary slightly in the range of interest. The misalignment between the top and bottom layers during fabrication or any other manufacturing error may be responsible for such discrepancies. The bandwidth of the power divider, where $S_{11} \leq -10$ dB and transmission coefficients are in the range -6.4 ± 0.5 dB between input and output ports, is 2.2 GHz from 2.5 GHz to 4.7 GHz.

Table 2 compares the performance of the presented power divider with previously reported SIW based power dividers. It is found to be about 40% smaller than the others.

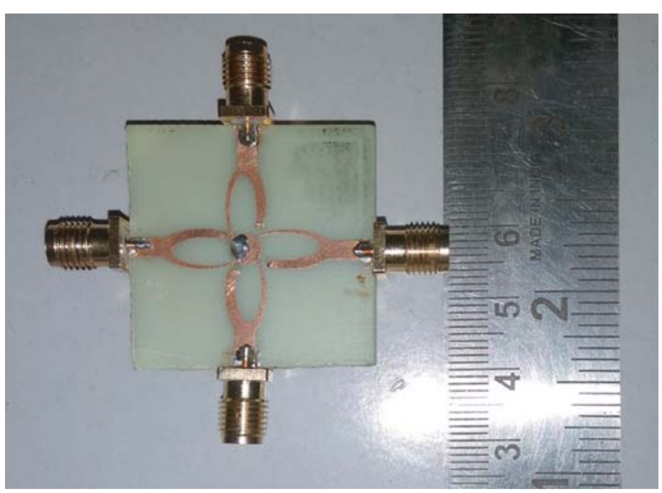

Figure 4. Photograph of the fabricated prototype.

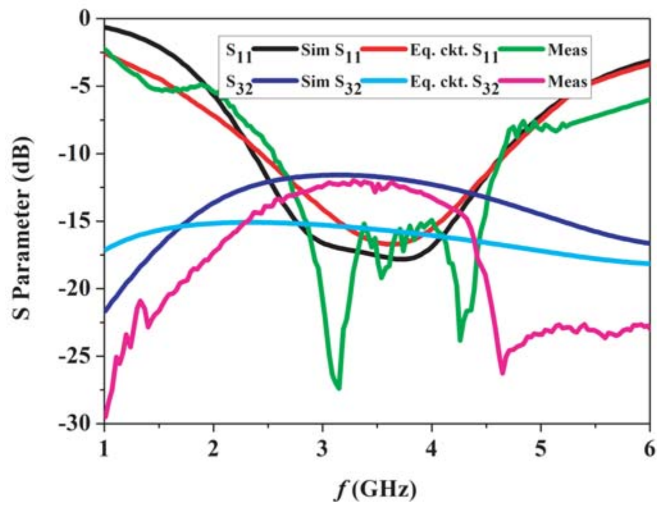

Figure 5. Isolation between two output terminals and return loss at input terminal.

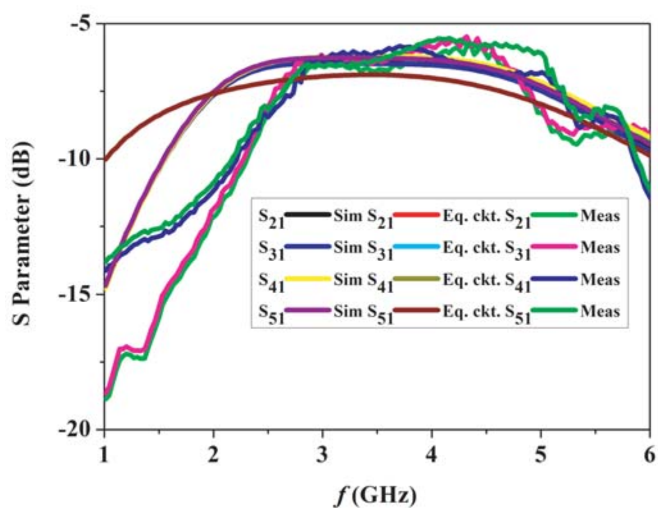

Figure 6. Insertion loss between input and output ports.

Table 2. Optimized design parameters

Ref.	f_0 (GHz)	Resonator type	Fractional BW	Size ($\lambda_g \times \lambda_g$)
[13]	5.5	SIW cavity	18%	0.95×0.95
[10]	10.9	SIW	1.8%	1.4×0.9
[11]	4.8	HMSIW/QMSIW	27%/11%	$0.7 \times 0.25/0.9 \times 0.25$
[12]	3.5	EMSIW	7.75%	0.8×0.8
[15]	2.4	1/32$^{\text{nd}}$ Mode SIW	39%	0.7×0.7
[19]	9.3	Multilayer	-	2.21×0.27
[20]	10	Multilayer	18	$2.3(\lambda_g^2)$
[21]	3.5	Multilayer	21.3	-
This Work	3.6	1/64$^{\text{th}}$ mode SIW	61%	0.55×0.55

4. CONCLUSION

In this paper, a novel compact 4-way power divider is discussed with the help of its equivalent circuit model. It uses $1/64^{\text{th}}$ mode elliptically curved SIW resonators to optimally utilize the space. The curvature of the resonator and other dimensions of the power divider are optimized to cover a wide frequency range from 2.5 GHz to 4.7 GHz, suitable for 5G communication. A prototype is designed, fabricated, and measured. The measured results are quite similar to the simulated ones. Its measured bandwidth is found to be 61%, and the maximum imbalance in the magnitude between output terminals is ± 0.5 dB in this frequency range. It occupies an area that is about 40% smaller than that of previously available SIW based power dividers, making it suitable for application in antenna array feeding networks.

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