Four-Way Substrate Integrated Waveguide (SIW) Power Divider/Combiner for High Power Applications

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***Abstract*-A four-way power divider/power combiner using substrate integrated waveguide (SIW) and microstrip lines is proposed and investigated. The proposed power divider consists of a double-layer substrate with a bottom layer including an SIW T-junction and a top layer including a microstrip network. This microstrip network consists of a modified Gysel power divider which provides a high isolation between output ports by using two grounded resistors. Meanwhile, this modified Gysel power divider maintains high power-handling advantage over Wilkinson power divider. A transition between the SIW T-junction and microstrip network is realized by etching two rectangular slots on the middle metal layer. The even-odd mode method is used to analyze the presented structure. A prototype of the proposed power divider is designed, simulated, and fabricated. The results show that the return loss of the input port is better than 12 dB over 8.43 to 10.57GHz. Also, the output return losses and isolation are better than 10.5 dB over the whole bandwidth.**

***Index Terms*-**Gysel power divider, high isolation, high power, power combiner, substrate integrated waveguide (SIW).

I. INTRODUCTION

The power divider has been widely used in many microwave and millimeter-wave systems as a key passive component in coupler, multiplexer, and antenna feeding systems, etc. [1-3]. Using a power divider, a microwave signal could be divided with an equal or unequal power division coefficient. In the microwave engineering, the T-junction H-plane waveguide power divider is a simple and widely used three-port network [4]. However, this type of power divider suffers from the disadvantage of not being matched at all ports, and it does not have isolation between output ports [3].

The Wilkinson power divider is a good choice to achieve good output matching and isolation between output ports [5]. These benefits are executed using a resistance branch. Also, the Wilkinson power divider has the advantages of low insertion loss and wide bandwidth but it is difficult to implement it with a large number of output ports. Moreover, it can not be used in high power

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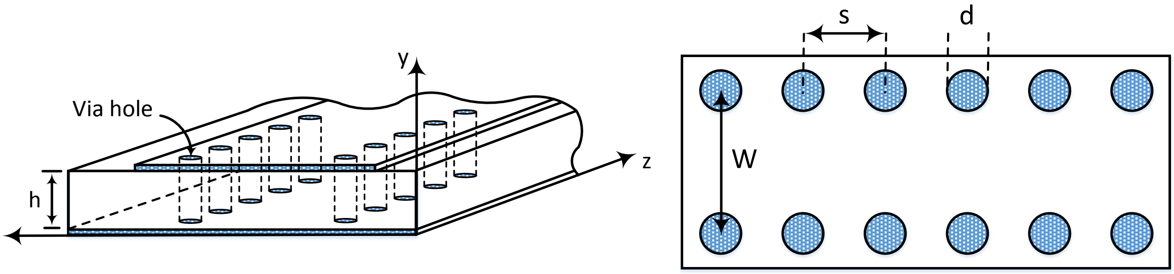


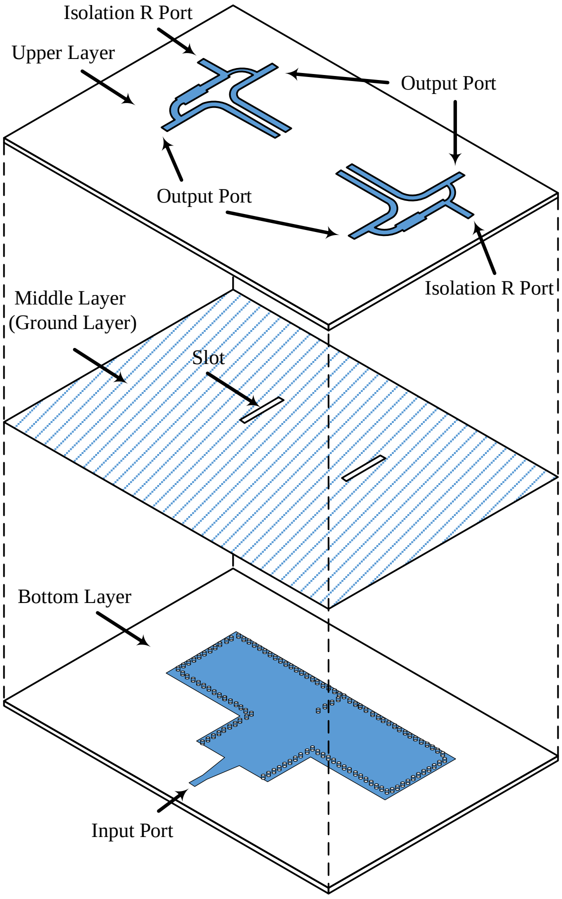
(a) (b)

Fig. 1. Configuration of the SIW structure (a) solid view (b) top view.

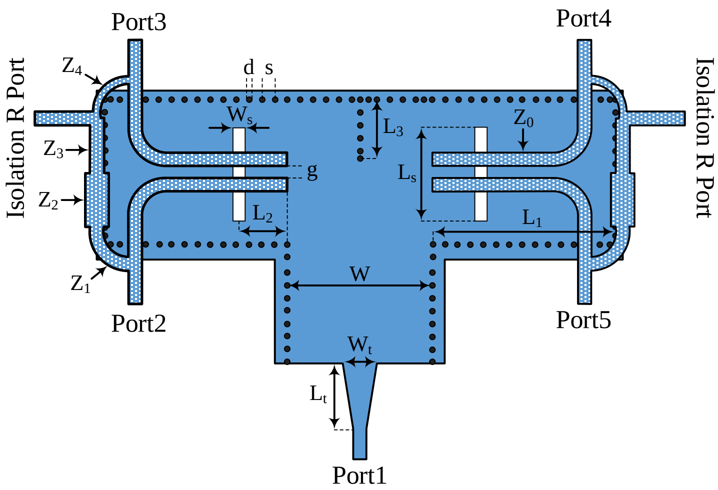
applications, because there is no way to transfer the generated heat to the surrounding media [6-8]. Therefore, the Wilkinson power divider is suitable for low power applications. As opposed to, the Gysel power divider is introduced for high power applications [6]. In this power divider, the generated heat could be transferred to the ground plane because of the grounded resistors.

The rectangular waveguide power dividers with the advantages of low loss, high Q value, and high power capacity have played very important roles in many microwave and millimeter-wave systems [9-12]. However, large size, high cost, and difficult integration with planar circuits limit their applications. Recently, the substrate integrated waveguide (SIW) has been introduced, based on two parallel rows of via holes in a metalized planar substrate as shown in Fig. 1 [13,14]. The SIW has many advantages, such as low cost, low loss, and easy integration with planar circuits [15]. Therefore, this structure is appropriate for the design of power divider/power combiner. In [16-20], several power dividers based on SIW technology have been investigated. In [16], an out-of-phase power divider based on a two-layer SIW is proposed. This power divider has a comparatively large insertion loss. In [17], a Y-junction four-way power divider is proposed by integrating a 90° Y-junction SIW power divider and a half mode substrate integrated (HMSIW) power divider. The proposed structure in [17] is suitable for wideband applications. However, it has a comparatively large insertion loss. Moreover, [16] and [17] suffer from the disadvantage of not being matched at all ports, and they do not have isolation between output ports. Among these SIW power dividers, two power dividers are reported in [18] and [19]. These structures have a good isolation between output ports. However, they are not suitable for high power applications because there is no way to effectively dissipate the heat generated by the resistor.

In this paper, a four-way power divider/power combiner using SIW and microstrip lines is presented. The proposed power divider consists of a double-layer substrate with a bottom layer including an SIW T-junction and a top layer including a microstrip network. In this microstrip network, a modified Gysel power divider using two grounded resistors is used, which provides a high isolation between output ports. Meanwhile, this modified Gysel power divider maintains high power-handling advantage over Wilkinson power divider. By etching two rectangular slots on the middle



(a)



(b)

Fig. 2. Configuration of the proposed structure (a) solid view (b) top view.

metal layer, a transition between the SIW T-junction and microstrip network is realized. The even-odd mode method is used to analyze the presented structure. A prototype of the proposed power divider is designed, simulated, and fabricated. In comparison with the previously published literature, the proposed structure can be used for high power applications because of the grounded resistors. The configuration of the proposed power divider is shown in Fig. 2.

II. DESIGN AND THEORY ANALYSIS

The proposed SIW power divider consists of an SIW T-junction, twelve microstrip branches, two isolation resistors, and two rectangular coupling slots etched on the middle metal layer. The SIW is a quasi-rectangular waveguide which only TE_{n0} modes can be propagated and the TE_{10} mode is the dominant mode. In this structure, The TM modes cannot be guided due to the dielectric gaps created by the via separations [21]. The cut-off frequency of the dominant mode can be determined by [22]:

$$f_{c(TE_{10})} = \frac{c}{2W_{eff}\sqrt{\mu_r \varepsilon_r}} \tag{1}$$

where c is the velocity of light in the free space, ε_r is the relative permittivity of the substrate, μ_r is the relative permeability of the substrate, and W_{eff} refers to the equivalent width of the SIW which can be calculated by [23]:

$$W_{eff} = W - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{W} \tag{2}$$

In (2), d refers to the diameter of the vias, s is their longitudinal spacing, and W displays the transverse spacing of the two vias that they are located at both sides of the SIW. A short wall in the end of SIW with a distance of $\lambda_{gs}/2$ ($\lambda_{gs}/2$ is the waveguide wavelength of the SIW at the center frequency) besides the slot is chosen to terminate the SIW end to satisfy the resonance condition and cause to cut off the SIW surface current by the slot, effectively [19]. In the microstrip network, the initial characteristic impedances and electrical lengths for the twelve branch-line sections are (Z_0, $\theta_0 + \theta_m$), (Z_1, θ_1), (Z_2, θ_2), (Z_3, θ_3), and (Z_4, θ_4). The coupling coefficient and impedance matching are determined by the slot length (L_s), slot width (W_s), and its location (L_2), which can be achieved through simulation [19].

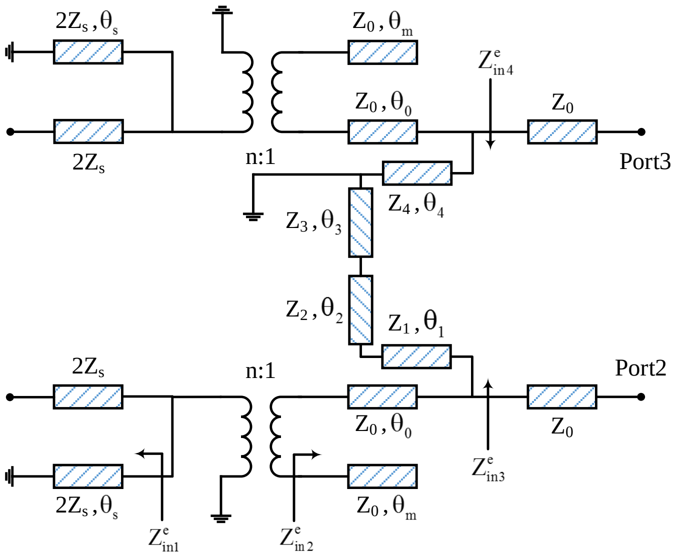
Fig. 3a shows the equivalent circuit of the SIW power divider when it is under even-mode excitation. Z^e_{in1}, Z^e_{in2}, Z^e_{in3}, and Z^e_{in4} can be calculated by following equations:

$$Z^e_{in1} = j2Z_s \tan\theta_s \tag{3}$$

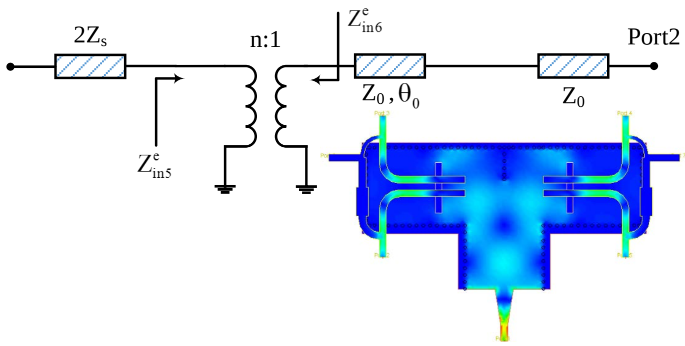
$$Z^e_{in2} = -jZ_0 \cot\theta_m \tag{4}$$

$$Z^e_{in3} = \frac{jZ_1(Z_1Z_3\tan\theta_1\tan\theta_2\tan\theta_3 - Z_1Z_2\tan\theta_1 - Z_2^2\tan\theta_2 - Z_2Z_3\tan\theta_3)}{Z_2^2\tan\theta_1\tan\theta_2 + Z_2Z_3\tan\theta_1\tan\theta_3 + Z_1Z_3\tan\theta_2\tan\theta_3 - Z_1Z_2} \tag{5}$$

$$Z^e_{in4} = jZ_4 \tan\theta_4 \tag{6}$$



(a)



(b)

Fig. 3. (a) Even-mode equivalent circuit and (b) simplified even-mode equivalent circuit of the proposed SIW power divider.

When $\theta_0 = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_m = \theta_s = \pi/2$, and $Z_0 = 2Z_s/n^2$, then $Z^e_{in1} = \infty$, $Z^e_{in2} = 0$, $Z^e_{in3} = \infty$, $Z^e_{in4} = \infty$, and the even-mode equivalent circuit can be simplified to the circuit shown in Fig. 3b. Also, Fig. 3b shows the current distribution of the proposed structure. The input impedance at port 1 and port 2 can be given by:

$$Z^e_{in5} = n^2 Z_0 = 2Z_s \tag{7}$$

$$Z^e_{in6} = 2Z_s / n^2 = Z_0 \tag{8}$$

Then, good input/output impedance matching can be obtained.

Fig. 4a shows the equivalent circuit of the SIW power divider when it is under odd-mode excitation. Z^o_{in1} can be calculated by:

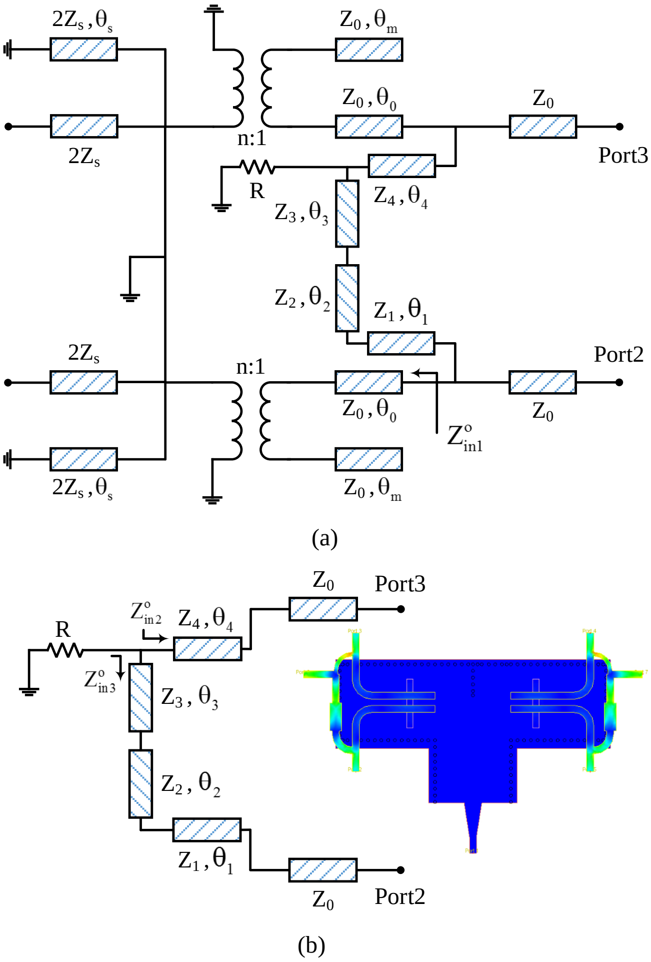


Fig. 4. (a) Odd-mode equivalent circuit and (b) simplified odd-mode equivalent circuit of the proposed SIW power divider.

$$Z_{in1}^{o} = \frac{-jZ_0(\cot\theta_m - \tan\theta_0)}{\cot\theta_m \tan\theta_0 + 1} \tag{9}$$

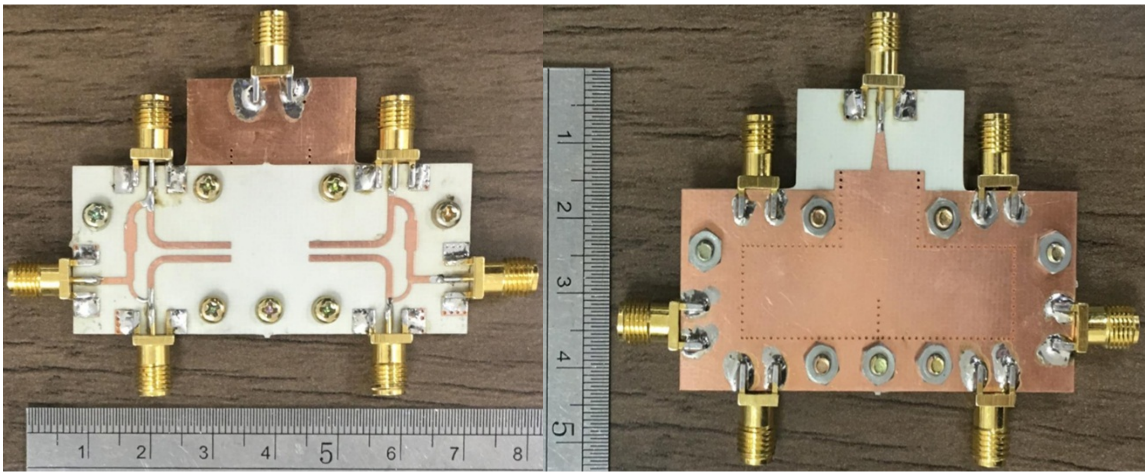
When $\theta_0 = \theta_m = \pi/2$, then $Z_{in1}^{o} = \infty$, and the odd-mode equivalent circuit can be simplified to the circuit shown in Fig. 4b. Also, Fig. 4b shows the current distribution of the proposed structure. In this case, the first part of the input impedance as seen from the position of the isolation resistor because of the circuit connected to Port 2 is:

$$Z_{in2}^{o} = \frac{Z_4^2}{Z_0} \tag{10}$$

The second part of the input impedance as seen from the position of the isolation resistor because of the circuit connected to Port 3 is:

Table I. Parameters of the proposed structure

Parameter	Value (mm)	Parameter	Value (mm)
W	12	Lt	5.4
Wt	2.8	Ls	7.75
Ws	1.11	g	1
L1	15.05	d	0.5
L2	4	s	1
L3	4.9		



(a) (b)

Fig. 5. Photograph of the proposed structure (a) top view (b) bottom view.

$$Z_{in3}^{o} = \frac{1}{Z_0}\left(\frac{Z_1 Z_3}{Z_2}\right)^2 \tag{11}$$

When R=Z_0, then $Z_{in2}^{o} = Z_{in3}^{o} = 2Z_0$ and $Z_4 = \sqrt{2}Z_0$. Moreover, according to [24], the values of Z_1, Z_2, and Z_3 are Z_0, $Z_0/\sqrt{2}$, and Z_0, respectively. The structure parameters have been optimized using ADS software and are listed in Table I.

III. RESULTS

In this paper, a Rogers RO4003C substrate with a relative dielectric constant of 3.55, thickness of 0.508 mm, and loss tangent of 0.0027 is used. The photograph of the proposed structure is shown in Fig. 5. Fig. 6 depicts the simulated and measured results of the proposed structure. The measured results show that the return loss of the input port is better than 12 dB over 8.43 to 10.57 GHz with 22.5% bandwidth. Also, the output return losses and isolation are better than 10.5 dB over the whole bandwidth. The simulated insertion losses are between 0.6 and 0.9 dB and the simulated phase unbalances are $\pm 3^{\circ}$. The measured insertion losses and phase unbalances are bigger than the

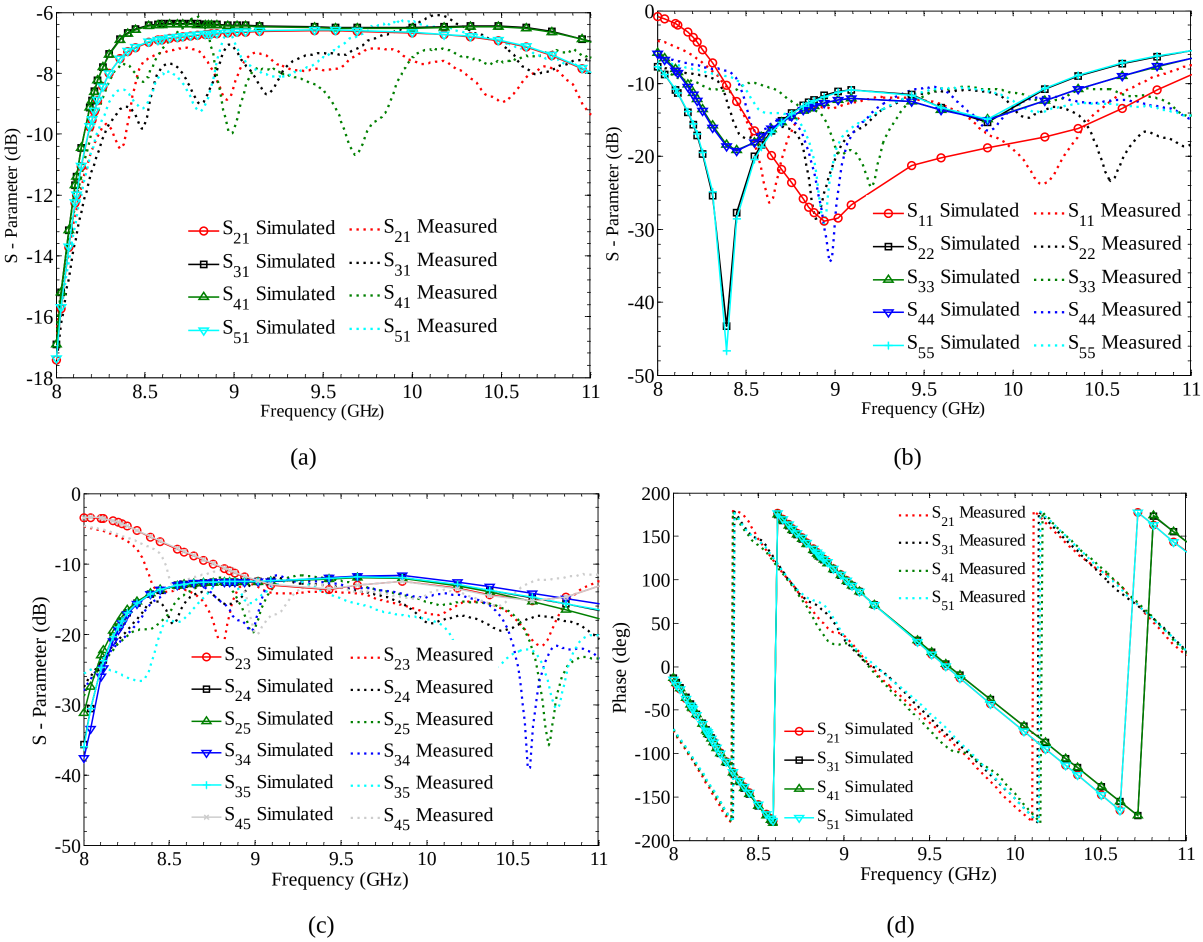


Fig. 6. Simulated and measured (a) insertion loss (b) return loss (c) isolation between output ports (d) phase.

Table II. Type sizes and appearance

Reference	Number of output ports	Bandwidth	Isolation/dB	Structure	Power capacity
[16]	4	6%	--	SIW slot coupling	high
[17]	4	39.2%	--	SIW Y-junction	high
[18]	2	20%	>13	Ring-shaped SIW	low
[19]	4	8.73%	>11.5	SIW slot coupling	low
This work	4	22.5%	>10.5	SIW slot coupling	high

caused by the insertion loss of SMA connectors, air gaps between two substrates and displacement errors in horizontal directions. Table II gives a comparison between the proposed power divider and other power dividers. The bandwidth and power capacity of the proposed power divider are better than [18] and [19]. Moreover, [16] and [17] suffer from the disadvantage of not being matched at all ports, and they do not have isolation.

IV. CONCLUSION

In this paper, a four-way power divider/power combiner using substrate integrated waveguide (SIW) and microstrip lines has been presented. Compared to the previously introduced structure, this power divider can be widely used in millimeter-wave systems and microwave because of its bandwidth and power capacity.

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