A Wide-Band Multiport Planar Power-Divider Design Using Matched Sectorial Components in Radial Arrangement

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***Abstract*—This paper proposes a new multiport planar power-divider design by radially combining the sectorial components and the input and output matching networks. This design can achieve good input match over a wide bandwidth without resorting to transformer sections of high-impedance lines, which are difficult to realize. This approach is applied to the design of 4- and 14-way center-fed power dividers in microstrip structures with good input match (voltage standing-wave ratio (VSWR) <1.5) over a bandwidth of 30% and 15%, respectively. The return loss of output ports and the isolation among them in the 14-way divider are less than −13 dB. A simple analysis method using the radial transmission-line theory to model the microstrip sectorial components is employed to characterize the power dividers. The calculated scattering parameters are found to be in good agreement with the measured data.**

***Index Terms*—Microwave passive circuit, power divider, radial transmission line.**

I. Introduciton

PASSIVE power dividers/combiners have been used extensively in microwave and millimeter-wave applications. For instance, they have been used in antenna-array feeding networks to distribute signals into a number of equal-phase outputs. Also, they have been used in solid-state power-amplifier circuits for combining several signals to obtain a signal output of large power.

Various designs for power dividers/combiners have been proposed in the literature [1]. They can be separated into two categories: those which combine the output of N devices in a single step (called N-way power dividers/combiners), and those which accomplish the power combining in several steps via a chain (serial) or tree (corporate) configuration. Generally speaking, the former can achieve higher combining efficiency since the power generated does not have to pass several combining stages. One of the oldest and well known of these structures is the Wilkinson N-way divider/combiner, for which the topology is nonplanar if $N > 2$ [2].

To cope with the development of prevailing printed circuits technology, many N-way power dividers/combiners are implemented in planar form. They can be subdivided into two groups—i.e., the "sector" and "radial" types, shown in Fig. 1(a) and (b), respectively. Sector-type dividers are truly planar and have the capability of nonequal output power levels at different ports [3], [4]. On the other hand, radial-type dividers, which are usually coaxially fed, have perfect balance in both magnitude and phase of the output signals at any frequency due to their geometrical symmetry [5], [6].

One of the major challenges in designing dividers is to minimize the return loss over a wide operating bandwidth. Theoretically, this problem can be solved by including sev-

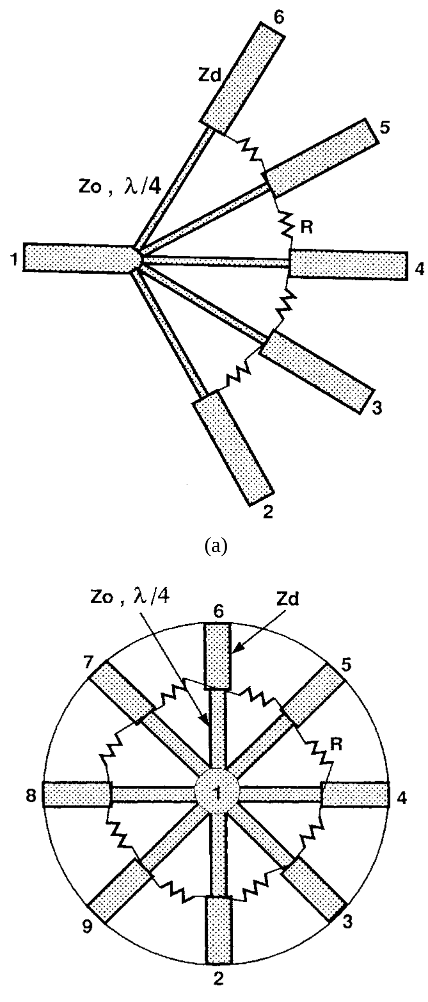

Fig. 1. The planar N-way power divider/combiner. (a) Sector type. (b) Radial type.

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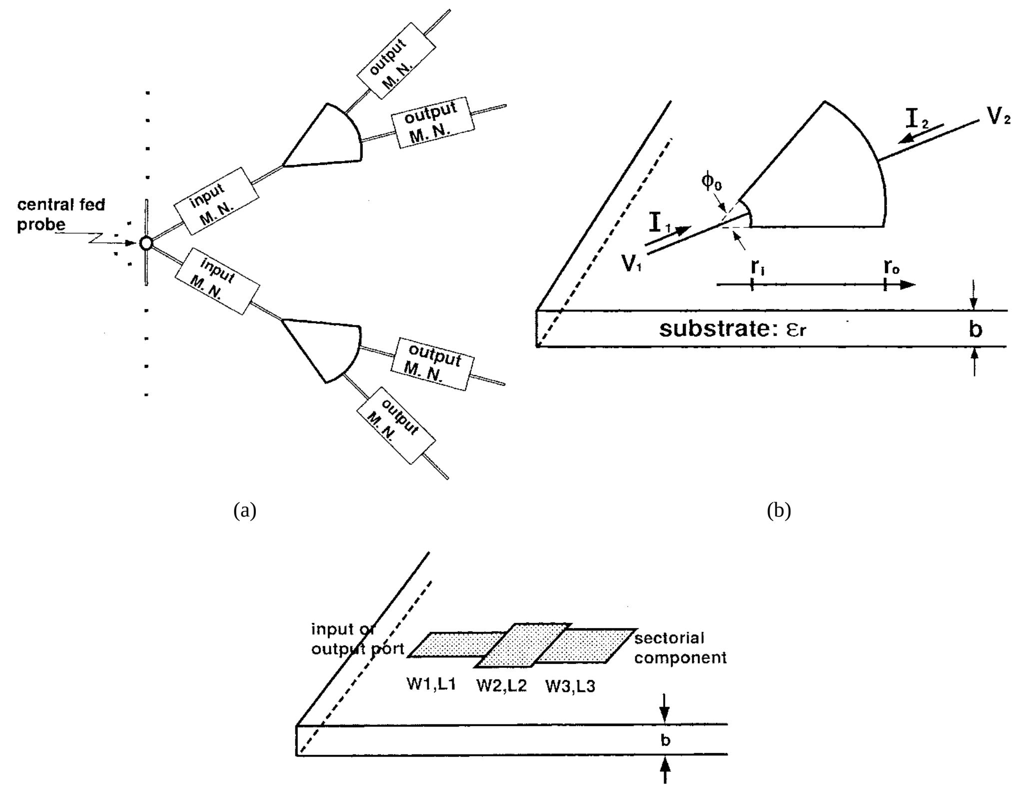

(c)

Fig. 2. The proposed power divider design. (a) Entire topology. (b) Geometry of the microstrip sectorial component. (c) Geometry of the input or output matching network.

eral transmission-line sections of different impedances for impedance matching. However, the matching will require a larger range of impedance levels if either the number of output ports N or the desired bandwidth increases. In practice, these impedance levels are difficult to realize due to limitations in the achievable linewidths in microstrip or stripline transmission media. For example, Hanczor and Kumar [6] proposed a 14-way power divider using maximally flat two-transformer sections. The 14 ports (50 Ω) are first combined in pairs, setting up several lines each at a 25-Ω level. The 25-Ω lines are transformed up to 350 Ω through the two-section maximally flat transformer. The seven parallel 350-Ω lines provided a 50-Ω input at summing points, thereby achieving an impedance match to 50 Ω. From the schematic of the 14-way power divider, they adopted two quarter-wavelength sections of characteristic impedances 37 and 140 Ω. A line with characteristic impedance of 140 Ω is not realizable in microstrip or stripline media unless special substrates are used.

In Section II of this paper, we propose a new topology which can alleviate the limitation of linewidth in design of N-way power dividers with large N and wide bandwidth. The topology is composed of several matched sectorial components in a radial arrangement. The sectorial component is analyzed by using the radial transmission-line approach [7], which is generalized to handle an arbitrary sector angle. Section III presents two design examples and discusses the improvement in bandwidth obtained by the addition of the input and output matching networks. The resultant 14-way power-divider design is fabricated and measured, exhibiting good characteristics over a wide bandwidth. Finally, brief conclusions are drawn in Section IV.

II. Description of Topology and Method of Analysis

The N-way power divider proposed in this paper possesses the topology shown in Fig. 2(a). It consists of four parts:

1) radial fan-out from the center-fed probe;
2) input matching network;
3) sectorial component;
4) output matching network.

The geometry of sectorial component is shown in Fig. 2(b). It may connect one input port to one output port and serve as an impedance transformer. It may even connect one input port to two or more output ports and provide an additional power-dividing stage. Note that the topology may reserve its pure symmetry if the number of output ports connected to each sectorial component is no more than two. The geometry of the matching network is shown in Fig. 2(c). It is made of three transmission-line sections of different impedance levels and lengths.

Although a detailed full-wave analysis based on a mixed-potential integral-equation formulation has been developed for arbitrarily shaped microstrip structures [8], it is too numerically intensive to deal with the present divider structure. A simpler and better approach to aid the divider design is necessary. Here, we employ transmission-line theory to deal with the matching networks and radial transmission-line theory to handle the sectorial component.

Radial transmission-line theory is covered in detail in the literature [7], [9]. Although originally developed for a disk, it is applicable to the sector-shaped component if the fringing field effects due to the open edges can be properly modeled. Consider the circuit of Fig. 2(b), in which a sector of spanning angle ϕ_0 and inner and outer radii r_i and r_o is printed on a substrate of height b and dielectric constant ϵ_r. It has been proposed that in order to give accurate results when compared with experimental data, the sector dimensions should be suitably enlarged and the underlying substrate should be replaced with a material of equivalent relative permittivity $\epsilon_{\rm eq}$ [10]. The inner and outer radii r_i and r_o are enlarged to become effective inner and outer radii r_{ie} and r_{oe} by using [11, eqs. (1) and (2)].

The impedance matrix elements for the equivalent sectorial component, with port 1 at the inner periphery and port 2 at the outer periphery, are then given in [9]

$$\begin{aligned} Z_{11} &= \jmath \frac{r_{oe}}{r_{ie}} \frac{C_s}{Sn} Z_o \\ Z_{12} &= Z_{21} = \jmath \frac{r_{oe}}{r_{ie}} \frac{Z_o}{Sn} \\ Z_{22} &= \jmath \frac{cs}{Sn} Z_o \end{aligned} \tag{1}$$

where

$$\begin{aligned} Z_o &= \frac{\eta b}{\phi_0 r_{oe}} \\ Sn &= \frac{\pi k r_{oe}}{2} [Y_1(kr_{ie}) J_1(kr_{oe}) - J_1(kr_{ie}) Y_1(kr_{oe})] \\ Cs &= \frac{\pi k r_{oe}}{2} [Y_0(kr_{ie}) J_1(kr_{oe}) - J_0(kr_{ie}) Y_1(kr_{oe})] \\ cs &= \frac{\pi k r_{oe}}{2} [J_1(kr_{ie}) Y_0(kr_{oe}) - Y_1(kr_{ie}) J_0(kr_{oe})]. \end{aligned}$$

The wavenumber k and intrinsic impedance η in (1) are given by

$$k = \omega \sqrt{\epsilon_0 \epsilon_{\rm eq} \mu_0} \quad \eta = \sqrt{\frac{\mu_0}{\epsilon_0 \epsilon_{\rm eq}}} \tag{2}$$

where ϵ_0 and μ_0 represent the permittivity and permeability in free space, respectively.

If the feeding line is a coaxial probe, the inner radius r_i is chosen to be the radius of the probe. If the feeding line is a microstrip line, the effective inner radius is related to the effective width $W_{\rm eff}$ by

$$r_{ie} = \frac{W_{\rm eff}}{2 \sin\left(\frac{\phi_0}{2}\right)} \tag{3}$$

in which the effective width is given by the well-known formula [12]

$$W_{\rm eff} = \frac{120\pi b}{Z_o \sqrt{\epsilon_{re}}} \tag{4}$$

where Z_o and ϵ_{re} represent the characteristic impedance and effective dielectric constant, respectively, of the microstrip line.

Since the structure is centrally fed by a coaxial probe, there is a discontinuity between the probe and radial line junction. In the design of the power divider/combiner, the junction effect is evaluated by using the Williamson model, in which the parameters of the equivalent circuit are obtained by employing the TEM analysis for the electric field in the coaxial aperture [13].

III. Experimental and Theoretical Results

Since the topology proposed here has angular symmetry, it will not exhibit any amplitude and phase imbalance among the output ports when operating as a power divider. In addition, the sectorial component is included to improve the impedance match. The very narrow lines resulting from impedance-matching requirements over a wide bandwidth for large N can be avoided by properly selecting the angle and radius of the sectorial component. Two examples are included to demonstrate the design procedure. In the realization, the power dividers are all designed in microstrip medium with substrate dielectric constant of 4.33 and height of 1.5 mm. The output 50-Ω transmission lines which are 2.89-mm-wide microstrip lines.

A. Four-Way Power Divider Without Matching Network

The first example is a four-way power divider in microstrip medium. The power incident from the center-fed probe is divided into four 50-Ω transmission lines through four sectorial components, without input or output matching networks. The sectorial component works like a tapered transmission line, thereby performing an impedance transformation from the central probe to the output port. The radius of the inner periphery r_i is chosen to be the radius of the center-fed probe. The radius of the outer periphery r_o is such that the sectorial component is nearly resonant (i.e., $J_1(k_o r_o) \cong 0$ where $k_o = 2\pi f_o \sqrt{\mu_o \epsilon_o \epsilon_{\rm eq}}$) at the center frequency f_o. Then, the impedance looking from outer radius r_o into the center-fed port is plotted versus the sector angle ϕ_0, from which ϕ_0 can be determined to minimize the return loss at the center frequency.

In the present case, consider the center frequency $f_o = 3.3$ GHz and inner radius $r_i = 1.0$ mm. From the requirement $J_1(k_o r_o) \cong 0$, the outer radius $r_o = 26.6$ mm is determined. By varying the sector angle ϕ_0, the impedance at the output port looking into the central probe is $50 \cdot N = 200\ \Omega$, as shown in Fig. 3. The imaginary part of the impedance is zero at $\phi_0 = 27.4°$. The real part is about 58 Ω, a good impedance match to the output port.

The scattering parameters of the four-way power divider with the outer radius 26.6 mm and sector angle $\phi_0 = 27.4°$ are shown in Fig. 4, with the experimental data also shown. It is in good agreement with the theoretical prediction calculated by applying (1).

B. Four-Way Power Divider with Both Input and Output Matching Networks

As shown in Fig. 4, the sectorial component can achieve a good input match only over a narrow bandwidth. To improve the bandwidth, it is helpful to first investigate the equivalent impedance seen from the output port into the sectorial component versus the outer radius r_o at operating frequency $f_o = 3.3$ GHz. In this case, the impedance curve at $r_o = 26.6$ mm has a sharp slope (see Fig. 5). This means that a slight

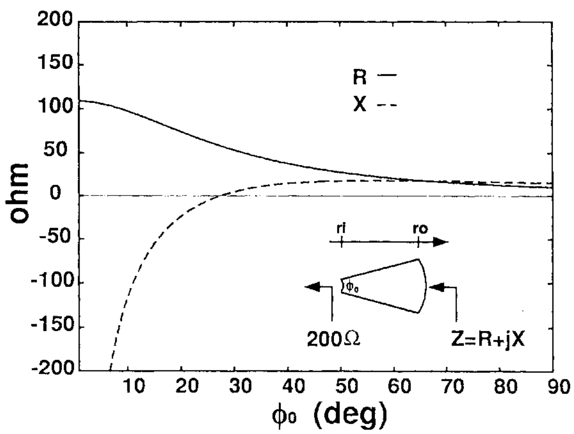

Fig. 3. The impedance of the sectorial component of the four-way power divider seen from the outer port versus the sector angle ϕ_0 at frequency $f_o = 3.3$ GHz. The outer radius r_o is 26.6 mm.

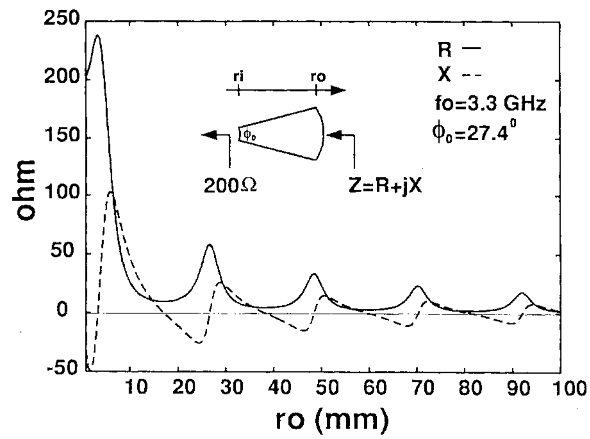

Fig. 5. The impedance of the sectorial component of the four-way power divider seen from the output port versus the outer radius r_o.

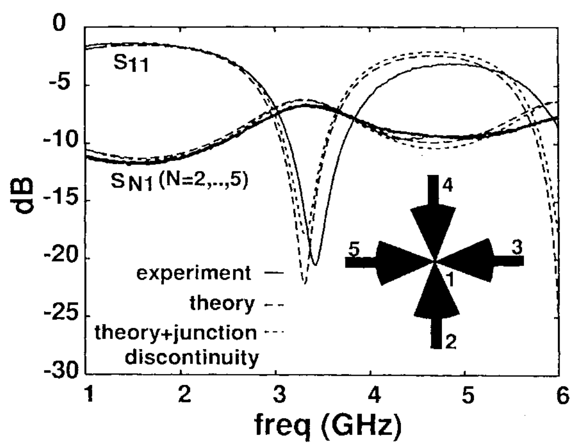

Fig. 4. Calculated and measured S_{11} and S_{N1} ($N = 2, 3, 4, 5$) versus frequency for a four-way power-divider design without matching network. The geometrical parameters on sectorial component: $\phi_0 = 27.4°$, $r_i = 1.0$, $r_o = 26.6$ mm.

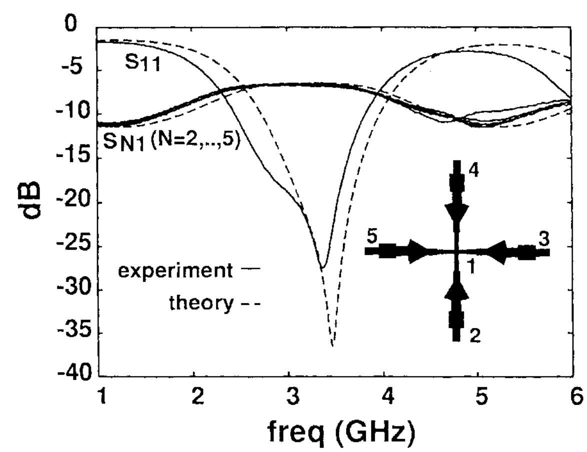

Fig. 6. Calculated and measured S_{11} and S_{N1} ($N = 2, 3, 4, 5$) versus frequency for a four-way power-divider design with matching networks. The geometrical parameters on input matching section (from probe to sector): $W_1 = 1.07, L_1 = 5.64, W_2 = 1.17, L_2 = 3.31, W_3 = 2.89, L_3 = 5$ mm; on sectorial component: $\phi_0 = 51.4°$, $r_i = 3.33$, $r_o = 15$ mm; on output matching section (from sector to output port): $W_3 = 4.96$, $L_3 = 5.94$, $W_2 = 6.97$, $L_2 = 5.89$, $W_1 = 2.89$, $L_1 = 10$ mm.

change in geometry or frequency will detune the resonant condition. As a result, the design using sectorial component only cannot exhibit a good impedance match over a wide frequency band.

This paper proposes a new wide-band design with the topology shown in Fig. 2. The design procedure starts with the selection of adequate radius and angle of the sectorial component for a flat impedance response. For example, r_o is chosen to be 15 mm, as evident from Fig. 5, where the sectorial component is nearly resonant, but the impedance level is comparatively flat. The impedance curves versus r_o with different sector angles ϕ_0 have been investigated. Although not shown here, the curve can become flatter if a larger ϕ_0 is chosen, say, $\phi_0 = 51.4°$.

Given the geometric parameters, the generalized impedance matrix of the sectorial component can be extracted by (1). Then, the impedance matrix is put into the commercial software HP-EEsof[1] to design the input and output matching networks for optimizing the bandwidth of the total topology. Initially, all sections in both the input and output matching networks are chosen to be one-eighth wavelength while the impedances are determined by three-section eighth-wavelength transformer design [14]. The section lengths and impedances are then optimized so as to maximize the bandwidth in the frequency band over which the return loss is small, e.g., voltage standing-wave ratio (VSWR) <1.5. For the present case, it takes about 10 min to achieve the optimized design using HP-EEsof at the Sparc-10 workstation.

The scattering parameters of the four-way power divider with both input and output matching networks are shown in Fig. 6. The theoretical and experimental results are in good agreement. The bandwidth of the power divider has been significantly enlarged by adding input and output matching networks. Based on the criterion of VSWR <1.5, the bandwidth is as wide as 30.8%.

C. 14-Way Power Divider Without Matching Network

The second example considers the design of a 14-way power divider, for which it is more difficult to achieve good input match due to a larger N (i.e., larger change of impedance

[1] Hewlett-Packard, *User's Guide for HP EEsof High-Frequency Design Solutions,* HP part E4605-90030, Santa Rosa, CA.

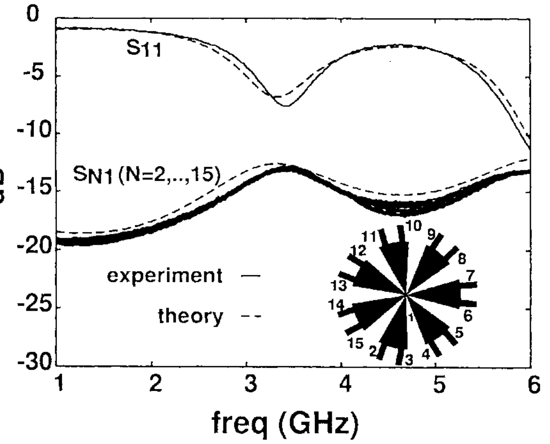

Fig. 7. Calculated and measured S_{11} and S_{N1} $(N = 2, 3, \cdots, 15)$ versus frequency for a 14-way power-divider design without matching network. The geometrical parameters on sectorial component $\phi_0 = 41.4°$, $r_i = 1.0$, $r_o = 26.6$ mm.

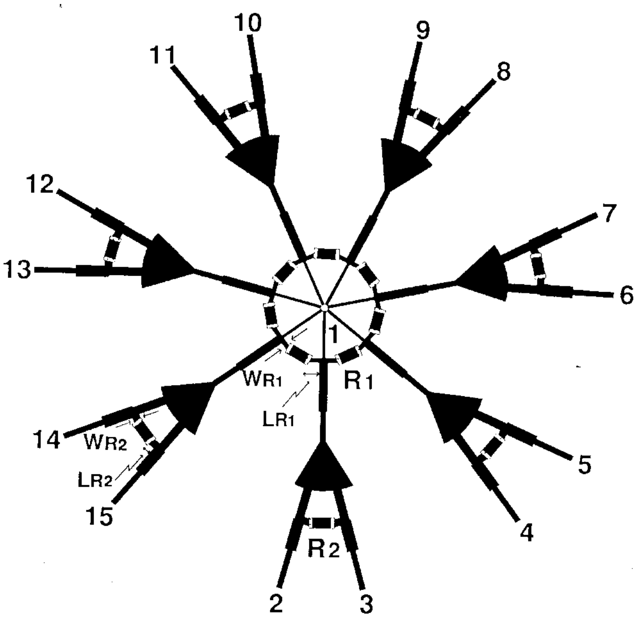

Fig. 8. The planar 14-way power divider/combiner with chip resistors.

level). To solve this problem, a two-stage design is employed. First, the input signal is divided into seven ports radially, then the sectorial component divides each port into two ports.

The design procedure of the 14-way power divider without matching network is the same as in Section III-A. Given the operating frequency $f_o = 3.3$ GHz and output radius $r_o = 26.6$ mm, the input impedance seen from the output port versus the sector angle has been investigated. It is worth noting that the angle ϕ_0 cannot be too large to make two adjacent sectors overlap. A good choice to minimize the return loss is found to be $\phi_0 = 41.4°$. The impedance seen from the output for this design is about 64 Ω, which is too high to match the output port impedance of $50/2 = 25$ Ω.

The scattering parameters of the power divider are shown in Fig. 7. Theoretical and experimental results are in good agreement. However, the reflection coefficient S_{11} is not satisfactory in the frequency range of interest as predicted. This shows that the input match is more difficult to achieve

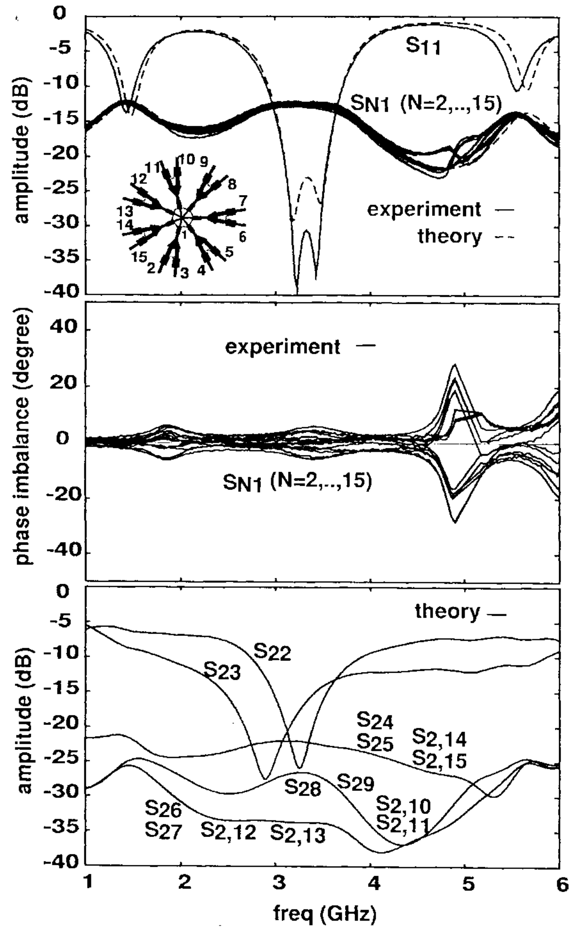

Fig. 9. Calculated and measured S-parameters versus frequency for a 14-way power-divider design with matching networks. The geometrical parameters on input matching section (from probe to sector): $W_1 = 0.50$, $L_1 = 14.0$,$W_2 = 4.36$, $L_2 = 12.4$, $W_3 = 2.89$, $L_3 = 5$ mm; on sectorial component: $\phi_0 = 51.4°$, $r_i = 3.33$, $r_o = 15$ mm; on output matching section (from sector to output port): $W_3 = 4.80$, $L_3 = 7.35$, $W_2 = 8.19$, $L_2 = 7.84$, $W_1 = 2.89$, $L_1 = 10$ mm. The presence of W_{R_1}, L_{R_1}, W_{R_2}, L_{R_2} is neglected in the analysis and optimization.

when the number of output ports N is large and only sectorial components are used.

D. 14-Way Power Divider with Both Input and Output Matching Networks

A wide-band design for the 14-way power divider can be accomplished by using the new topology shown in Fig. 2(a). According to the aforementioned design procedure, we select adequate outer radius $r_o = 15$ mm and sectorial angle $\phi_0 = 51.4°$. The input and output matching sections are designed after an optimization. Typically, the isolation among output ports can be improved by including proper isolation resistors, as illustrated in Fig. 8. The values of the resistors in the two stages are optimized by using the commercial computer-aided design (CAD) software HP-EEsof. They are found to be $R_1 = 62$ Ω and $R_2 = 35$ Ω.

The scattering parameters of the resultant 14-way power divider are shown in Fig. 9. Both the theoretical and experimental results are shown and found to be in good agreement. It can be verified that the power divider exhibits low return loss, ideal amplitude and phase balance, and good port isolation

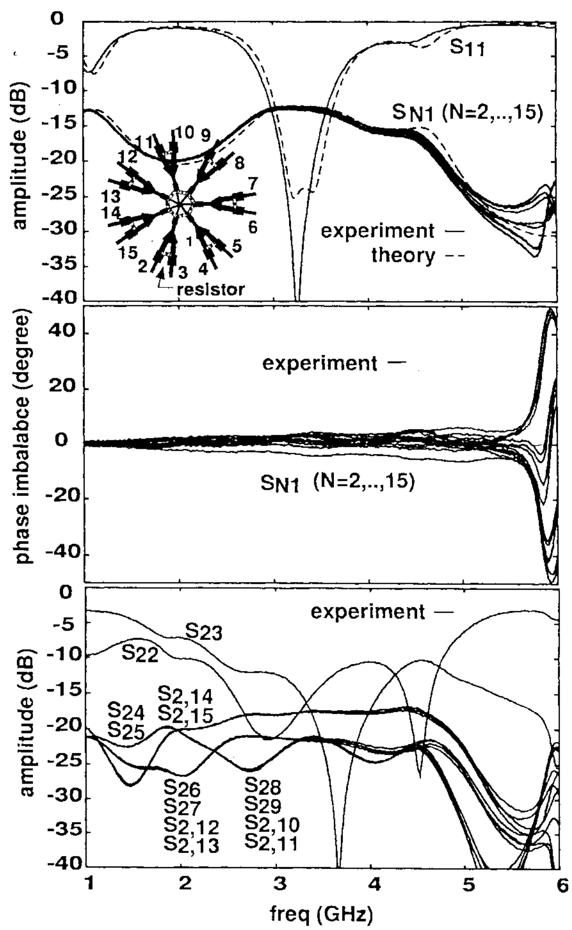

Fig. 10. Another design for a 14-way power divider with matching networks. The geometrical parameters on input matching section (from probe to sector): $W_1 = 1.06$, $L_1 = 13.95$, $W_2 = 2.83$, $L_2 = 14.99$, $W_3 = 2.89$, $L_3 = 5$ mm; on sectorial component: $\phi_0 = 51.4°$, $r_i = 3.33$, $r_o = 15$ mm; on output matching section (from sector to output port): $W_3 = 3.89$, $L_3 = 3.91$, $W_2 = 5$,$L_2 = 4.89$, $W_1 = 2.89$, $L_1 = 10$. The small sections for the connection of isolation resistors are such that $W_{R_1} = 2.59$, $L_{R_1} = 4.95$,$W_{R_2} = 4$, and $L_{R_2} = 2.3$ mm.

in the frequency band of interest. For the criterion of VSWR <1.5 (or $|S_{11}| < -14$ dB), the bandwidth is 15.7% centered at frequency 3.3 GHz. Over this bandwidth, the imbalance is measured to be less than ±0.6 dB in amplitude and ±5.02° in phase. The return loss at all circumferential ports and the isolation among them are less than −13 dB. Hence, this design is also suitable to serve as a power combiner.

In contrast, Hanczor and Kumar designed a 14-way power divider of similar performance [6]. Their design called for quarter-wave transformer sections with impedance level as large as 140 Ω. Such a high impedance line is quite difficult to realize in practical geometry if the substrate is present. However, in the present design, the characteristic impedance of the matching transmission-line sections is at most 109 Ω, which is easier for realization by most transmission-line configurations, e.g., microstrip lines.

It is possible to further reduce the highest impedance level of the transmission lines in the matching sections. As Fig. 10 shows, the scattering parameters of another design has the highest impedance level of 82.9 Ω and chip resistors $R_1 = 30\ \Omega$, $R_2 = 100\ \Omega$. Here, the small sections for the connection of chip resistors (i.e., W_{R_1}, W_{R_2}, L_{R_1}, L_{R_2} in Fig. 8) are also put into the optimization. Thus, the design can still achieve good input match, but with a slight decrease in bandwidth as the tradeoff. The amplitude imbalance is measured to be ±0.37 dB and phase imbalance ±4.98° in the frequency band 3–3.5 GHz. Although having a much wider bandwidth, the present design can still yield comparable performance to the previous design in [6], in which the amplitude and phase imbalance are measured to be ±0.2 dB and ±6°, respectively, in the frequency band 2.7–2.9 GHz.

However, the return loss of all circumferential ports and the isolation among them are found to be less than −12 dB. This is worse than the design in [6], where the isolation is measured to be −18 dB. The worst isolation happens between two ports of the same sectorial component, which also makes the design narrow banded compared to the isolation between other ports. To be more specific, consider ports 2 and 3. When the two ports operate at the differential mode, a significant amount of the incident current at port 2 will flow into port 3. The presence of isolation resistor R_2 between ports 2 and 3 can absorb the undesired leaky current satisfactorily for a limited frequency range only.

IV. Conclusions

This paper has proposed a new topology of N-way power divider that achieves high bandwidth without resorting to transmission-line sections of too wide or too narrow linewidth. The topology is basically radial, which maintains perfect balance among the output ports. It includes sectorial components to provide the impedance transformation as well as an additional power-dividing stage. Also, input and output matching networks formed with transmission-line sections of different impedance levels and lengths are inserted to improve input match. A simple analysis method based on radial transmission-line theory is employed to obtain the impedance matrix of the sectorial components, which is then used with the aid of CAD software to design the matching networks.

The new topology is employed in design of 4- and 14-way power dividers in microstrip medium. In each example, the design with matching networks can achieve good input match over a wide bandwidth. For the criterion of VSWR <1.5, the achievable bandwidth is 30% and 15% for the 4- and 14-way power dividers, respectively. These power dividers were fabricated and measured. The measured and predicted results are in good agreement. It is verified that the design based on the new topology can achieve perfect balance of output powers, low return loss, and good isolation over a wide bandwidth, even when the number of output ports is large.

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