Efficient Wideband Power Divider for Planar Antenna Arrays

(*Invited Paper*)

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Abstract — Power dividers with a good match over a wideband of frequencies are designed using Klopfenstein impedance taper for use with wideband antenna arrays. To validate the proposed design procedure a 2-way stripline, and a 2-way microstrip power divider are designed, fabricated, and measured. The measured return loss reveals better than –24 dB (from 4.3 GHz to 19.5 GHz) match for the 2-way stripline, and –27 dB (from 2.2 GHz to 12 GHz) match for the 2-way microstrip. Then a single Klopfenstein taper is used in the design of a 4-way stripline power divider. Measurements reveal return loss better than –22 dB (from 2.3 GHz to 19 GHz) for the 4-way stripline power divider. Furthermore, use of a single taper resulted in a shorter feed network compared to the traditional 4-way feed network using 2-way power dividers at two stages.

I. INTRODUCTION

Power dividers are passive RF components that are commonly used to split and distribute power in various proportions to different components of networks. Two major areas for power divider applications are (1) distribution of input signal to amplifiers and (2) distribution of RF signal to antenna arrays. Various types of power divider configurations have been introduced to support planar circuit applications. An overview of these configurations can be found in [1].

A branch-line type power divider, in combination with a quarter-wavelength transformer or a stepped transmission line transformer [2], is frequently employed in the feeding networks of planar antenna arrays. This kind of power divider supports narrow band operations due to limited bandwidth of the quarter-wave transformer. When it becomes necessary to feed a wideband antenna array, the corresponding power dividers should be capable to operate in a much wider bandwidth. For a good match, a return loss of -20 dB is desirable. Some configurations of branch-line circuits described in [1] have only a narrow frequency range (less than 10 %) in which the return loss is better than -20 dB. Others never reach this level of matching.

Various techniques have been proposed for the realization of wideband branch-line type power dividers. One of the methods is to employ wideband matching circuits to match the input line impedance to that of the junction. In [3] a 5-way wideband planar power divider is developed using a 4-section quarter wavelength transformer and shunt resistances for the wideband matching. In [4], 3 and 4 section quarter wavelength transformers are used to realize wideband characteristics. This paper demonstrates the use of Klopfenstein taper [5] for the design of wideband matching circuits and power dividers for printed antenna array applications. Typical length of the Klopfenstein impedance taper is about one-half wavelength at the lowest frequency, and the upper frequency limit is theoretically infinite. In comparison, a two-section quarter wavelength binomial impedance transformer [6, p. 313] can provide the return loss of -30 dB only in a 1.5:1 frequency ratio. As will be shown here, much wider frequency ratios are easily achievable in practice. Therefore, for a good match, the tapered impedance transformer is vastly superior to a multi-section quarter-wavelength transformer. This kind of taper was utilized in the design of 2-way finline power combiners in [7].

Section II gives the Klopfenstein equations used to design the tapers presented in this paper. Section III describes a 2-way power divider in stripline realization. Section IV describes a 2-way power divider in microstrip configuration. In Section V, a 4-way stripline power divider is proposed to reduce the feeding network length. Measurements show that it operates in about 8:1 frequency range. All designs have been first optimized by simulation software, and then fabricated and measured. In all three designs, the tapered section is designed for a -30 dB ripple, with the hope that the branching and 90-degree bend sections will not degrade the overall ripple significantly.

The effect of dispersion of microstrip lines on the bandwidth of the matching circuit is discussed. Sonnet[1] software package and a FDTD program developed by our group are used as electromagnetic simulation tools in the design process. Issues that are vital in accurate simulation and measurement of planar circuits are discussed, and guidelines are given as well. The extension of the proposed power divider design to

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[1] Sonnet Software, Inc., 100 Elwood Davis Road, North Syracuse, NY 13212.

applications with larger number of elements for antenna array systems is straightforward.

II. KLOPFENSTEIN EQUATIONS

For largest possible bandwidth with a fixed maximum magnitude of reflection coefficient, the input reflection coefficient ρ for a continuous taper takes the form [5]

$$\rho = \rho_0 \frac{\cos\left[\sqrt{(\beta l)^2 - A^2}\right]}{\cosh(A)} e^{-j\beta l} \tag{1}$$

where β is the wave number, and l is the taper length. The specification of the parameter A determines the maximum magnitude of reflection coefficient in the pass band which consists of all frequencies such that $\beta l \geq A$. The reflection coefficient magnitude takes on its maximum value $|\rho_0|$ at zero frequency, and it oscillates in the pass band with constant amplitude equal to $\rho_0/\cosh(A)$, which has been set to –30 dB for the current applications. The value of ρ_0 is calculated using $\rho_0 = 0.5 \times \ln(Z_2/Z_1)$, where Z_1 and Z_2 are the characteristic impedances at the ends of the taper. In [8] the variation of the characteristic impedance along the taper section is given by

$$\ln(Z_0(x)) = \frac{1}{2}\ln(Z_1 Z_2) + \frac{1}{2}\frac{\ln(Z_2/Z_1)}{\cosh(A)} \times \left[A^2\phi\left(\frac{2x}{l}, A\right) + U\left(x - \frac{l}{2}\right) + U\left(x + \frac{l}{2}\right) - 1\right] \tag{2}$$

where U is the unit step function, and ϕ is a function defined as

$$\phi(z, A) = \int_0^z \frac{I_1\left(A\sqrt{1-y^2}\right)}{A\sqrt{1-y^2}} dy, \qquad |z| \leq 1 \tag{3}$$

and I_1 is the first kind modified Bessel function of the first order.

III. 2-WAY STRIPLINE POWER DIVIDER DESIGN

In this section, the design of a wideband 2-way stripline power divider is demonstrated. The design mainly consists of two steps: the first is the design of a taper that will provide wideband matching between the 50 Ohms (Z_2) input line and 25 Ohms (Z_1) junction of output branches and the second is the design of the junction with very low return loss over a frequency band as wide as possible.

The Klopfenstein taper is ideally a smooth continuous transition; however for simulation purposes a 21 section stepped impedance transition of length $l \approx \pi/\beta$ is analyzed. For a desired return loss less than -30 dB the maximum reflection coefficient in the pass band is

$$\max(\rho) = 10^{-30/20} = 0.0316227\,. \tag{4}$$

For impedance transition from 50 Ohms to 25 Ohms $\rho_0 = 0.3466$. Since the pass band starts at $\beta l = A$, one can use this condition to calculate A from (1) along with the defined values of max(ρ) and ρ_0. The corresponding value of A is 3.0853 which is then used in (2) to compute the characteristic impedance of each section of the tapered line as listed in Table I. Rogers RT5880 laminate with dielectric constant 2.2, loss tangent 9×10^{-4}, and thickness 1.575 mm is used for the physical design. The physical dimensions of the sections of the taper that are matching to the impedances in Table I are determined by simulations using Sonnet and the line widths are listed in Table I. The lengths of individual sections are equal to 1 mm. Figure 1 shows the simulated taper while Fig. 2 shows simulation results compared to the theoretically expected curve which is calculated using (1).

Table I. Stripline taper design parameters for 50 Ω to 25 Ω transition with maximum –30 dB return loss.

Section	Z_0 (Ω)	Width (mm)	Section	Z_0 (Ω)	Width (mm)
input	50	2.60	11	35.355	4.25
1	48.383	2.75	12	33.930	4.50
2	47.565	2.80	13	32.582	4.75
3	46.589	2.90	14	31.337	5.00
4	45.465	3.00	15	30.198	5.25
5	44.209	3.15	16	29.167	5.45
6	42.834	3.30	17	28.275	5.70
7	41.393	3.45	18	27.493	5.90
8	39.889	3.65	19	26.830	6.05
9	38.361	3.80	20	26.280	6.20
10	36.841	4.05	21	25.836	6.35
			output	25	6.6

The observed very good match between the simulation results and the theory suggests that this taper can support a high pass operation above 4.9 GHz with a return loss better than –30 dB.

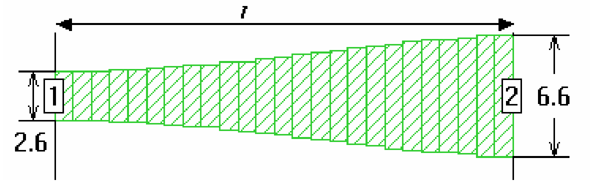

Fig. 1. Impedance taper as simulated in Sonnet.

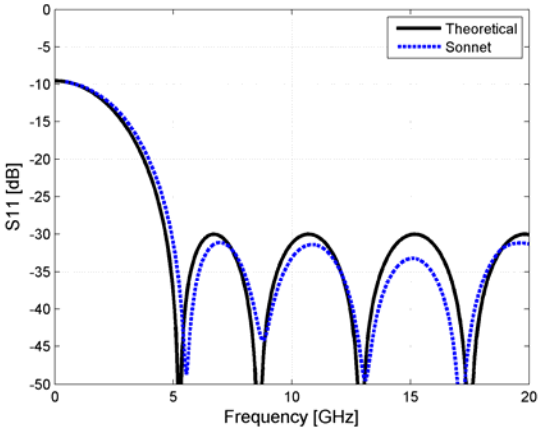

Fig. 2. Simulated return loss compared to theoretical curve.

Once the taper is designed, the next step is to design the junction branching from 25 Ω line to two 50 Ω lines. After a series of simulations the optimum dimensions for minimum return loss over a possible maximum bandwidth are determined. At this point an optimization technique could be employed to achieve an optimum design. The optimized dimensions are given in Fig. 3.

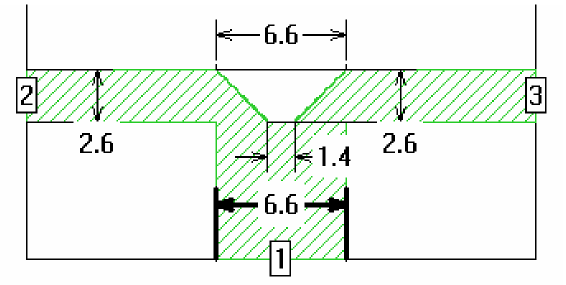

Fig. 3. Optimized junction from 25 Ω to two 50 Ω striplines (Dimensions are in millimeters).

The circuits in Figs. 1 and 3 are cascaded to form a stripline power splitter. The final design is manufactured as shown in Fig. 4. Figure 5 shows the measurements compared to simulation of the final design in Sonnet. The simulation result from Fig. 2 is also displayed in this figure in order to show the effect of the branching junction. Measured results demonstrate that the manufactured circuit is a good wideband power divider with a return loss better than –24 dB over a frequency band from 4.3 GHz to 19.5 GHz.

An accurate determination of return loss is a difficult task to achieve both in simulations and measurements. In the network analyzer measurement set up, time gating is used in order to eliminate the effect of the coaxial-to-stripline launchers from the circuit response. However, it has been realized that the input line was not long enough to eliminate the second reflection between the branching discontinuity and the input port. Thus, it can be inferred that if the input line was made longer, the actual response of the measured circuit may become even better than the one shown in Fig. 5.

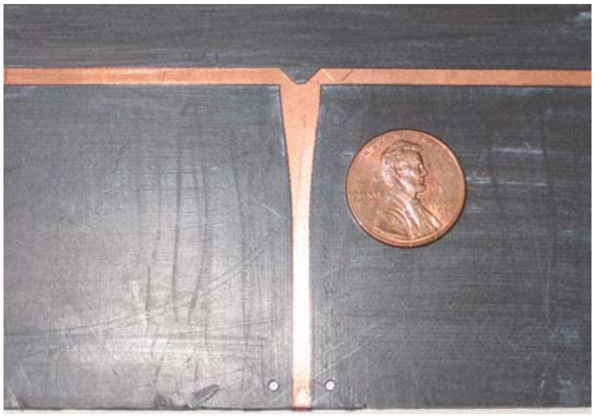

Fig. 4. Manufactured stripline power divider.

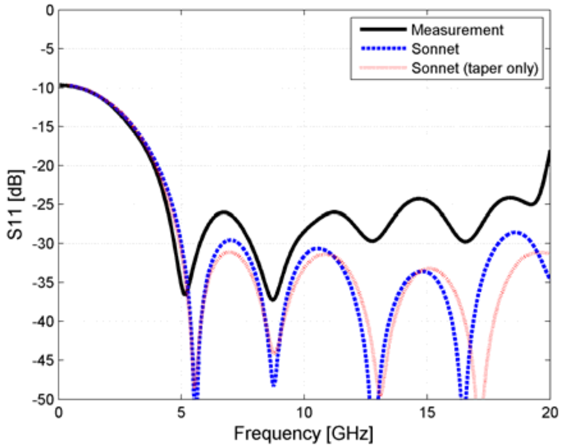

Fig. 5. Stripline power divider measurement compared to simulated return losses.

It is worth mentioning that the effect of conductor thickness also must be modeled for an accurate simulation [9]. As much as 1 Ω difference in the characteristic impedance of a line can be observed when the conductor thickness is taken into account.

IV. 2-WAY MICROSTRIP POWER DIVIDER DESIGN

In this section, a wideband power divider design is realized as a microstrip circuit. Microstrip lines are dispersive unlike striplines, and the frequency dependence of the characteristic impedances of microstrip lines imposes additional challenge on the design of a wideband taper. Since it is not possible to maintain constant impedance values over a very wide band, a taper would work the best around the frequencies where the impedance values in Table II are maintained. Therefore, the physical dimensions of the taper sections shall be calculated at the frequencies of interest. In the current design the section widths are calculated to satisfy characteristic impedances at frequencies around 8-10 GHz as given in Table II, and each section is 2 mm long.

Table II. Microstrip taper design parameters for 50 Ω to 25 Ω transition with maximum –30 dB return loss.

Section	Z_0 (Ω)	Width (mm)	Section	Z_0 (Ω)	Width (mm)
input	50	1.80	11	35.355	3.00
1	48.383	1.88	12	33.930	3.20
2	47.565	1.96	13	32.582	3.36
3	46.589	2.04	14	31.337	3.56
4	45.465	2.08	15	30.198	3.72
5	44.209	2.20	16	29.167	3.96
6	42.834	2.28	17	28.275	4.08
7	41.393	2.40	18	27.493	4.24
8	39.889	2.52	19	26.830	4.36
9	38.361	2.68	20	26.280	4.48
10	36.841	2.84	21	25.836	4.56
			output	25	4.80

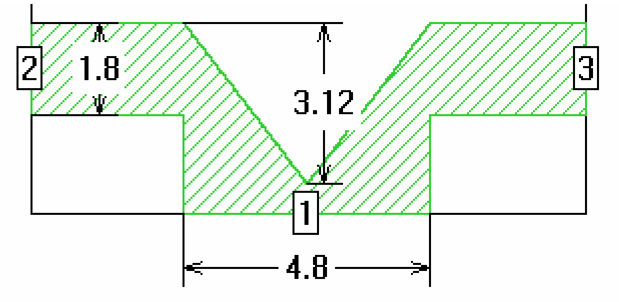

Fig. 6. Optimized junction from 25 Ω to two 50 Ω microstrip lines. (Dimensions are in millimeters)

The Gil GML1000 laminate of relative dielectric constant 3.2, loss tangent 4×10^{-3}, and thickness 0.762 mm is used for the physical design. After a series of simulations the optimum dimensions for minimum return loss over a possible maximum bandwidth are determined. The optimized dimensions are given in Fig. 6. The taper and the junction circuit in Fig. 6 are cascaded to form a microstrip power divider. The final design is manufactured as shown in Fig. 7. As can be noticed from the picture, the input line length is kept long in order to perform a more accurate time-gated measurement. The measured return loss is compared to those obtained using Sonnet and FDTD simulations in Fig. 8. The measurement shows that a wideband 2-way microstrip power divider is realized with a return loss better than –27 dB from 2.2 GHz up to at least 12 GHz.

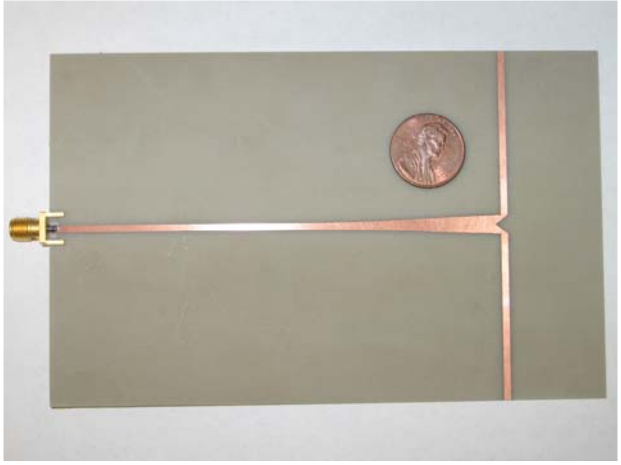

Fig. 7. Manufactured microstrip power divider.

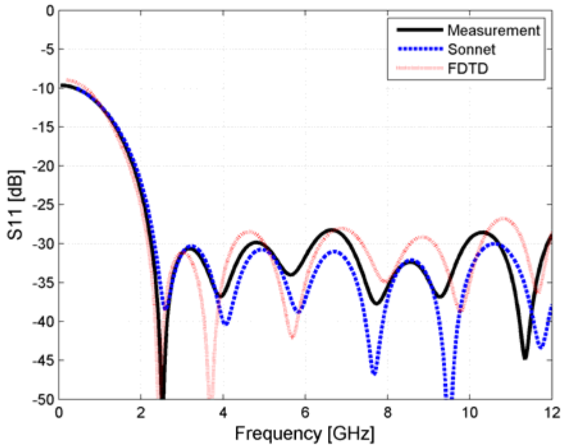

Fig. 8. Microstrip power divider measurement compared to simulated return losses.

V. 4-WAY STRIPLINE POWER DIVIDER DESIGN

The Klopfenstein taper can also be used to match impedances of junctions having more than two branches. In this section, the design of a 4-way stripline power divider is discussed. In the case of 4 output lines the 50 Ω input line impedance shall be matched to 12.5 Ω. The impedance values for a 21 section taper are listed in Table III. These impedances are determined such that a transition from 50 Ω to 12.5 Ω will have –30 dB return loss for the frequencies above which the taper length is 0.579 wavelength long. The widths of the sections, computed for a stripline using Gil GML1000 laminates with 0.762 mm thickness, are listed in Table III. After the taper design and simulation are completed, the junction with 12.5 Ω line input and two 25 Ω lines output is designed for minimum reflection for a frequency band as wide as possible. Then, the junction with 25 Ω line input and two 50 Ω lines output such as in Fig. 3 is added on each side. The final circuit is formed with the inclusion of optimally designed mitered bends. The fabricated circuit is displayed in Fig. 9, and the measurement and simulation results are shown in Fig. 10 together with the simulation of the taper alone. Comparing simulations it can be observed that although the taper provides a high pass operation, the branching sections slightly degrade the overall performance. The measurement still has a good agreement with simulation and shows a wideband performance with a return loss better than –22 dB between 2.3 GHz and 19 GHz.

Table III. Stripline taper design parameters for 50 Ω to 12.5 Ω transition with maximum –30 dB return loss.

Section	Z_0 (Ω)	Width (mm)	Section	Z_0 (Ω)	Width (mm)
input	50	0.90	11	25.000	2.45
1	48.206	0.95	12	22.784	2.80
2	46.862	1.00	13	20.809	3.10
3	45.157	1.05	14	19.082	3.45
4	43.112	1.15	15	17.602	3.80
5	40.773	1.25	16	16.357	4.15
6	38.210	1.40	17	15.329	4.50
7	35.507	1.55	18	14.497	4.80
8	32.753	1.75	19	13.841	5.05
9	30.036	1.95	20	13.337	5.30
10	27.431	2.20	21	12.965	5.45
			output	12.5	5.70

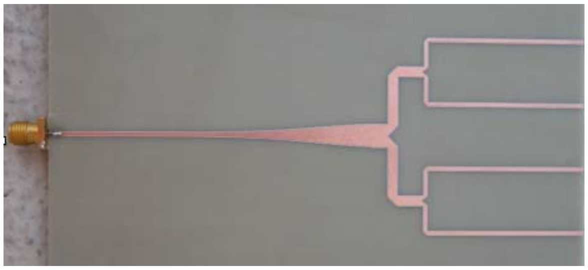

Fig. 9. Fabricated wideband 4-way stripline power divider.

One of the advantages of this 4-way power divider design is that only one taper is used to achieve power division to four outputs. Therefore, the length of the network is shorter than a conventional power divider that uses 2-way power dividers at two stages to achieve four outputs. The network path being short provides compactness as well as less attenuation while feeding the antenna arrays. The return loss achieved by this design is higher than those obtained from 2-way power dividers designed in previous sections. This difference is acceptable since the 4-way power divider is a more complicated design, and the return loss includes the combined effect of two power-dividing stages, mitered bends and the taper. Therefore it is feasible to use this approach for designing power division networks with higher number of ports with a return loss better than -20 dB.

V. CONCLUSION

Wideband planar power dividers have been designed using Klopfenstein taper and their performances were verified through simulations and measurements. The presented designs exhibit two main advantages; wideband characteristics and reduced size-feeding network.

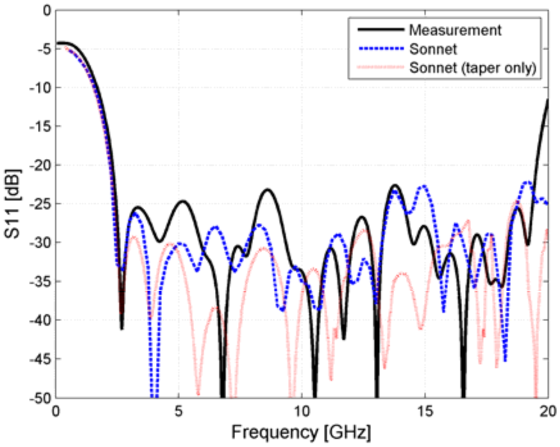

Fig. 10. Return loss of a 4-way stripline power divider.

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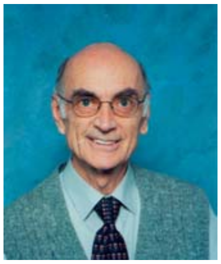

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