Philippine Engineering Journal (2000) XXI (1): 1-11

DESIGN AND CONSTRUCTION OF A BROADBAND WILKINSON POWER DIVIDER/COMBINER

Rolando C. Guevarra
Communications Engineering Division
Advanced Science and Technology Institute
Department of Science and Technology
Philippines

ABSTRACT

Power dividers, directional couplers, and hybrid junctions are passive microwave components used for power division or power combining. Power dividers often are of the equal-division (3 dB) type, but unequal power division ratios are also possible. This paper describes the design, construction and characterization of a low loss broadband Wilkinson power divider/combiner implemented in microstrip using low cost FR4 and metal film resistor. Major results include broadband DC–6 GHz frequency range, 0.0314 dB insertion loss above 3 dB, 38 dB isolation at the design frequency, 0.0^{o} phase unbalance, 0.0334 dB amplitude unbalance, and a 1.0694:1 VSWR.

I. Introduction

Power dividers/combiners offers a wide range of applications. This transmission line coupler style allows N-way equal amplitude and phase division of a signal. Since most passive network implementation is reciprocal, it can combine N in-phase sources into a single output (termed a combiner). This latter mode is useful in combining the output of N medium-power solid-state devices for high-power requirements and can be employed to combine a number of oscillators at a single port. Power combiners can combine multiple antennas in stacked antenna systems, while providing a constant 50 Ω impedance over the bandwidth chosen. Among the popular applications are power distribution module for phased antenna arrays, steerable antenna requiring N-way power division, low loss combination between 2 cellular stations, and high isolation in the GSM transmit band between the combine ports to protect the cell stations thereby avoiding intermodulation product generation. Front-end applications include low loss and high isolation power dividers for splitting receiver lines in order to feed two or more receivers. A low noise preamplifier is normally used ahead of the power divider to overcome the loss of the splitter and enhance system noise figure. By adding a filter ahead of the preamplifier a complete multi-coupler can be built. If there are more than four receivers in the system a combination of 2-way and 4-way power dividers will be required. Any unused outputs should be terminated with 50 Ω loads. Such passive circuits are employed when making wideband comparison measurements, power monitoring and as options for network analyzer applications. Unequal power division can also be achieved depending on the implementation.

In characterizing power dividers/combiners, some of the important specifications to be considered are the frequency of operation, i.e., ultra broadband and no tuning ever required, low insertion loss, low VSWR, high isolation, phase balance, amplitude uniformity, maximum power input as combiner/splitter, complete shielding and dimensions.

The Wilkinson divider is a matched three-port passive network in which a signal at port 1 is equally divided between the other two ports; its symmetry indicates that the phase angle at each output port is the same [1]. The structure is a hybrid junction because internally connected resistors provide isolation between output ports. This concept was utilized by Parad and Moynihan [2] to design a two-way power divider capable of unequal power division. The most widely used arrangement, however, is that of equal power division [3]. In an *N*-way divider, each port may be connected to a variable phase shifter and some suitable aperture. This transmission line coupler style allows *N*-way equal amplitude and phase division of a signal. Since the network is reciprocal, it can combine *N* in-phase sources into a single output.

With a brief discussion of Wilkinson power divider theory, circuit design for microstrip implementation will be introduced together with a discussion of the materials and methods used, discussion of results, conclusions and recommendations.

II. Wilkinson Power Divider Theory

One useful power divider met in microwave engineering is the Wilkinson three-port circuit illustrated in Figure 1. It has the property that its three port are matched, that the power at the input port is equally divided between the other two and that the two output ports are isolated.

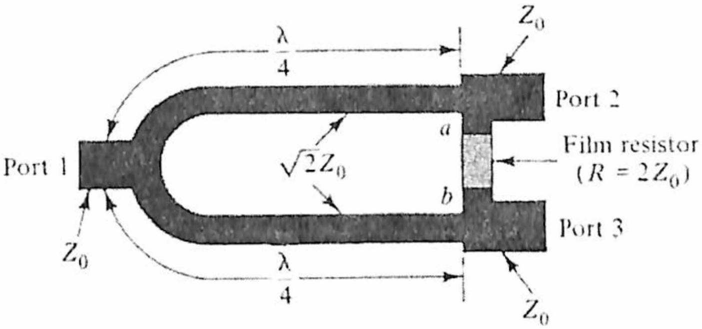


Figure 1. An equal-split Wilkinson power divider in microstrip form

The Wilkinson divider uses quarter-wavelength transmission lines emanating from a common input port to *N* outputs. The terminating resistors carry no current if all the port voltages are of equal amplitude and phase since their common node is not grounded. As will be shown, these resistors perform the function of providing isolation between output ports for signals reflected from unmatched loads. This is accomplished by canceling the reflected wave, which has

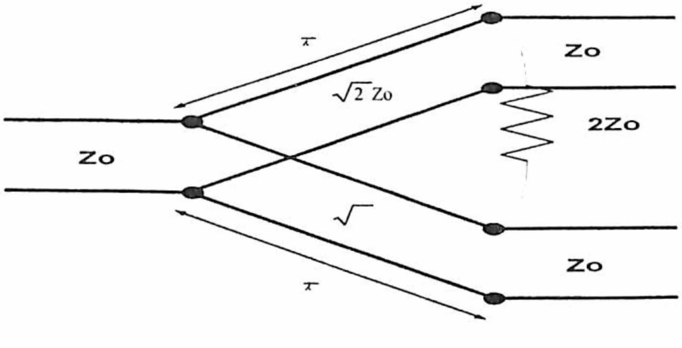


Figure 2. Equivalent transmission line circuit

been delayed π radians through the two quarter-wavelength transmission lines, with another equal amplitude wave through the resistors delayed 0 radians assuming resistors of zero length [4]. This divider is often made in microstrip or stripline form, as depicted in Figure 1; the corresponding transmission line circuit is given in Figure 2.

[5] derived the scattering matrix of a 3 dB Wilkinson Power Divider using the even-odd mode analysis. The results of his derivations were as follows:

$S_{11} = 0$ (lossless when the output ports are matched)
$S_{22} = S_{33} = 0$ (since ports 2 and 3 were matched for both modes of excitation),
$S_{12} = S_{21} = -j0.707$ (symmetry since reciprocal network),
$S_{13} = S_{31} = -j0.707$ (symmetry since reciprocal network),
$S_{23} = S_{32} = 0$ (because of short or open at bisections).

It is this last result that implies isolation between ports 2 and 3 [5, 6].

III. Circuit Design:

The actual circuit construction is a design issue in the Wilkinson power divider, especially in the layout for the resistor in between the output ports. Bends in the circuit may introduce a significant amount of capacitance, and if not properly addressed may contribute additional losses to the circuit. The equivalent circuit of a microstrip bend is illustrated in Figure 3.

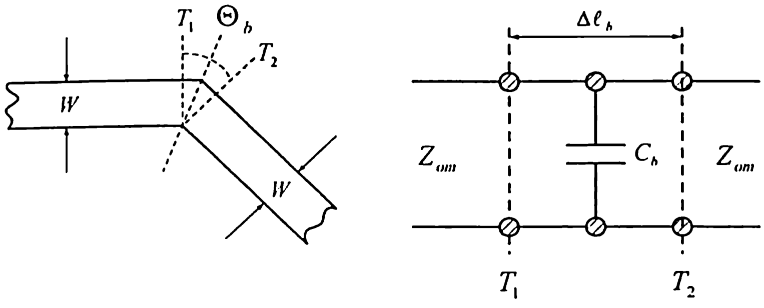


Figure 3. Geometry and Equivalent Circuit of a Microstrip Bend

Additional numerical data concerning discontinuity capacitance of microstrip angled-bend can be obtained from " Microstrip Lines and Slotlines" by Gupta [7].

In practical circuits, microstrip bends are chamfered (see Figure 4) to compensate for the excess capacitance. The exact details of chamfering vary from substrate to substrate, and unfortunately there are no theoretical computations for chamfered bends so far.

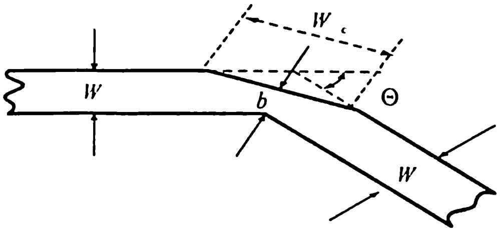


Figure 4. A Chamfered Bend

Concerning *right angle bends*, closed form expressions for capacitance and inductance introduced per unit length can be found from Thomson and Gopinath [8]. Silvester and Benedek [9] have computed the electrostatic value of the excess capacitance of right-angled bends.

Literatures would suggest the Wilkinson power divider configuration in Figure 1, rounded at the edge to eliminate the effect of microstrip discontinuities on the transmission line, but such a configuration would be very difficult to implement using traditional fabrication techniques.

Figures 5 to 7 details the microstrip implementation. Microstrip synthesis and simulation were done using Transmission Line Calculator [10] and Touchstone [11].

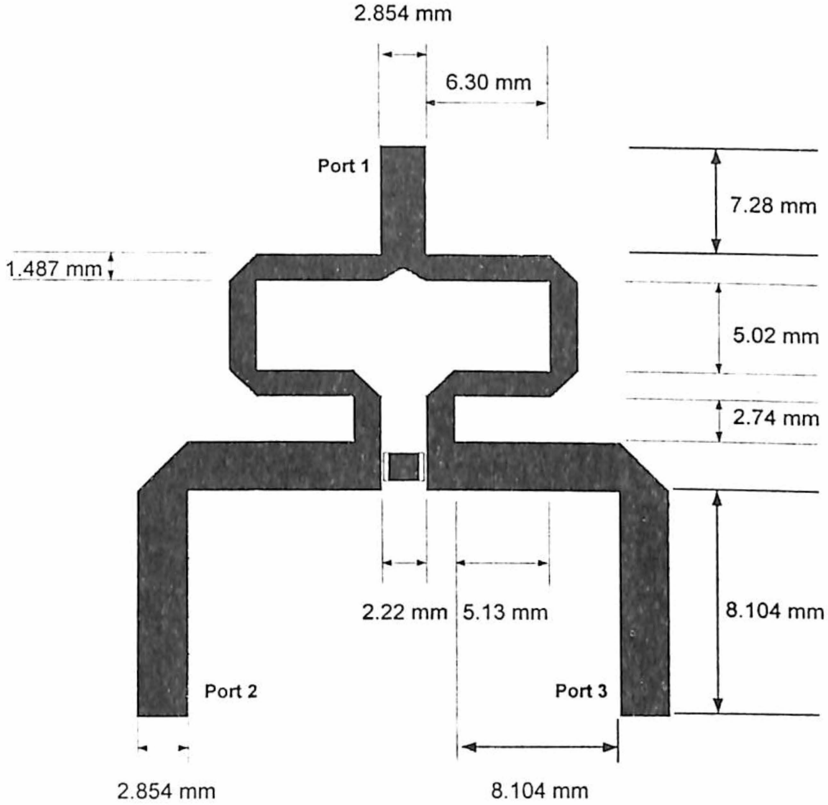
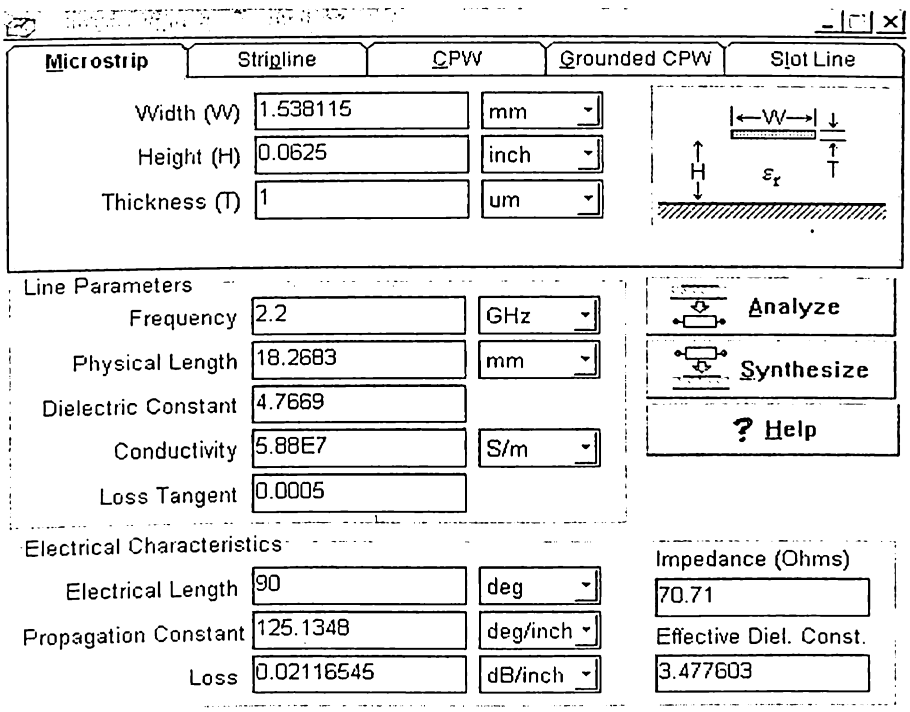


Figure 5. Details of the 2.2 GHz Wilkinson power divider/combiner.
Deviation from calculation is due to fabrication process



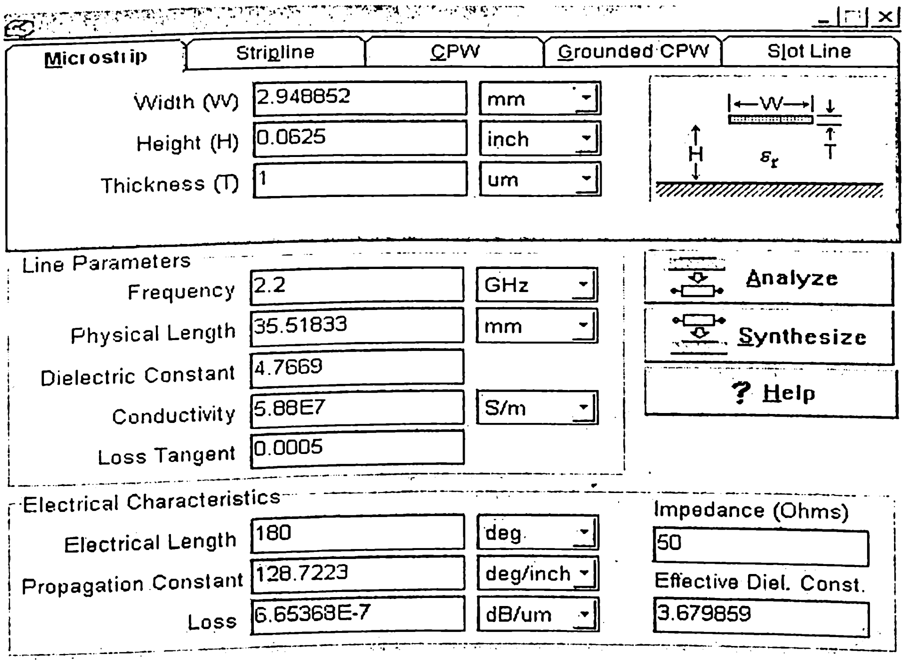
Width (W) 1.538115 mm
Height (H) 0.0625 inch
Thickness (T) 1 um

Line Parameters
Frequency 2.2 GHz
Physical Length 18.2683 mm
Dielectric Constant 4.7669
Conductivity 5.88E7 S/m
Loss Tangent 0.0005

Electrical Characteristics
Electrical Length 90 deg
Propagation Constant 125.1348 deg/inch
Loss 0.02116545 dB/inch

Impedance (Ohms) 70.71
Effective Diel. Const. 3.477603

Figure 6. Synthesis of the 70.71 Ω microstrip line



Width (W) 2.948852 mm
Height (H) 0.0625 inch
Thickness (T) 1 um

Line Parameters
Frequency 2.2 GHz
Physical Length 35.51833 mm
Dielectric Constant 4.7669
Conductivity 5.88E7 S/m
Loss Tangent 0.0005

Electrical Characteristics
Electrical Length 180 deg
Propagation Constant 128.7223 deg/inch
Loss 6.65368E-7 dB/um

Impedance (Ohms) 50
Effective Diel. Const. 3.679859

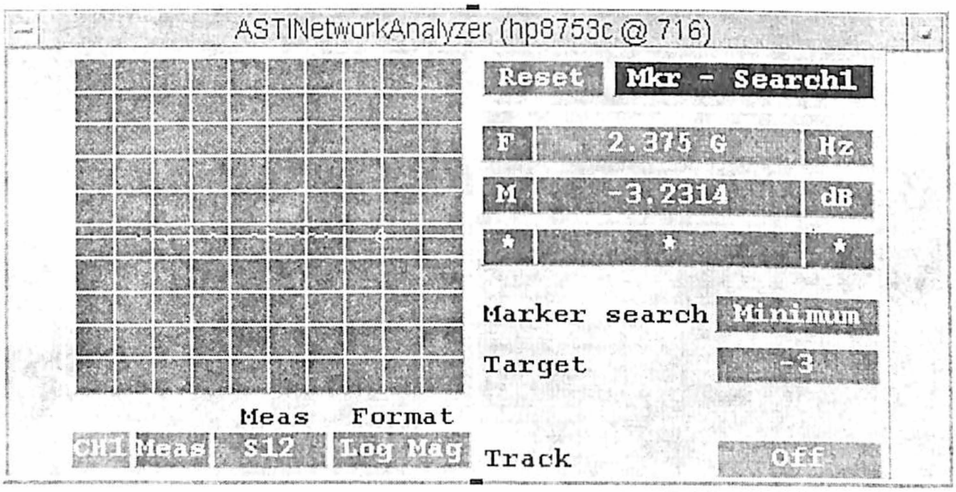
Figure 7. Synthesis of the 50 Ω microstrip line

IV. Materials and Methods

0.065 inch thick FR4 board was used with a dielectric constant of 4.7669. A 100 Ω metal film resistor was used to terminate the two quarter-wavelength 70.71 Ω lines while the three ports were terminated using 50 Ω SMA Female 4-Hole Panel Mount Solder Cup Contact. S parameter test and measurements were conducted using HP8753C and HP8719C Vector Network Analyzers whose calibration is set using 3.55 mm calibration kit.

V. Discussion of Results

Automated test and measurements were conducted using HP Virtual Engineering Environment software to control the HP 8753C Vector Network Analyzer via the HPIB. Figures 8 to 18 details the characterization. Take note that S_{21} and S_{12} label in the figure is relative to ports 1 and 2 of the vector network analyzer while as the S measurements are relative to designated ports of the Wilkinson power divider/combiner implementation.



ASTINetworkAnalyzer (hp8753c @ 716)

F 2.375 G Hz

M -3.2314 dB

Marker search Minimum

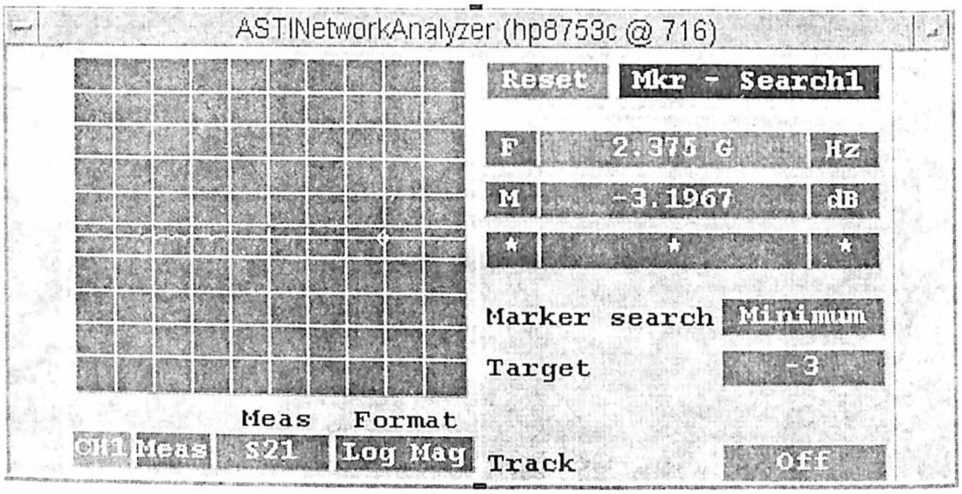
Target -3

Meas S12

Format Log Mag

Track Off

Figure 8. S_{21}



ASTINetworkAnalyzer (hp8753c @ 716)

F 2.375 G Hz

M -3.1967 dB

Marker search Minimum

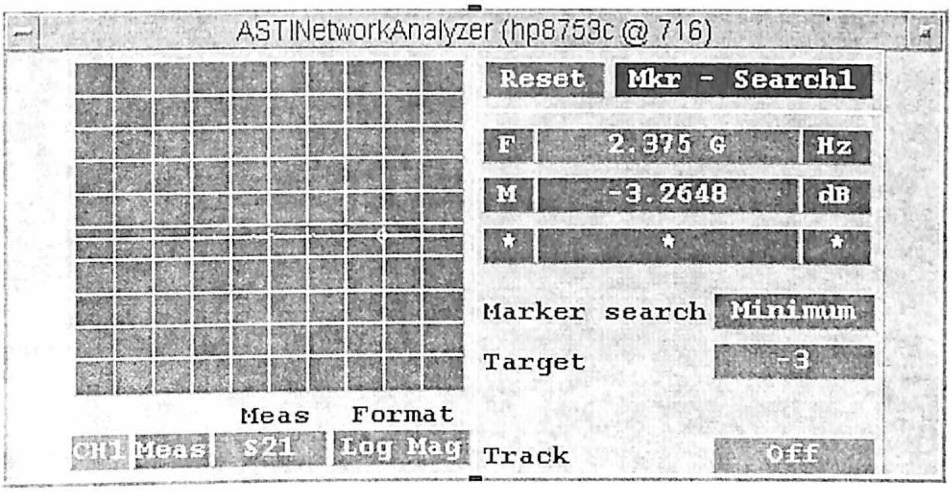
Target -3

Meas S21

Format Log Mag

Track Off

Figure 9. S_{12}


ASTINetworkAnalyzer (hp8753c @ 716)

Reset Mkr - Search1

F 2.375 G Hz

M -3.2648 dB

* * *

Marker search Minimum

Target -3

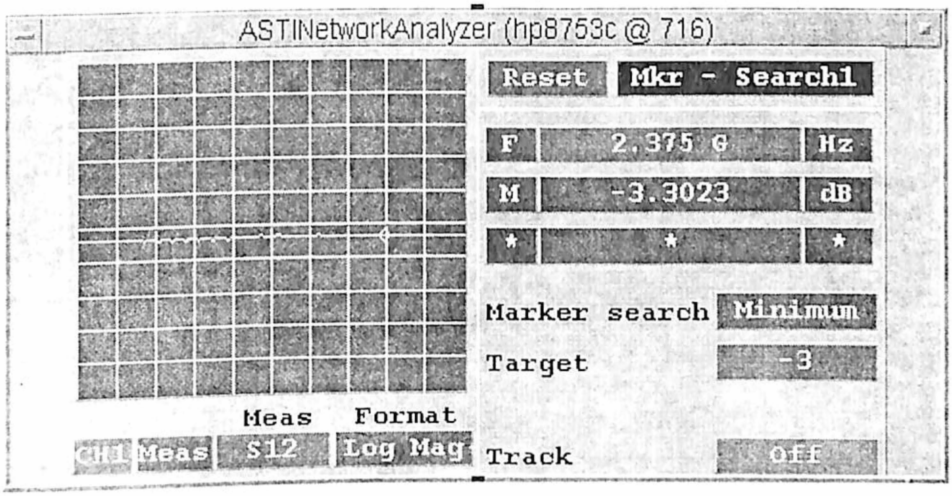
Meas S21

Format Log Mag

CH1 Meas

Track Off

Figure 10. S_{31}


ASTINetworkAnalyzer (hp8753c @ 716)

Reset Mkr - Search1

F 2.375 G Hz

M -3.3023 dB

* * *

Marker search Minimum

Target -3

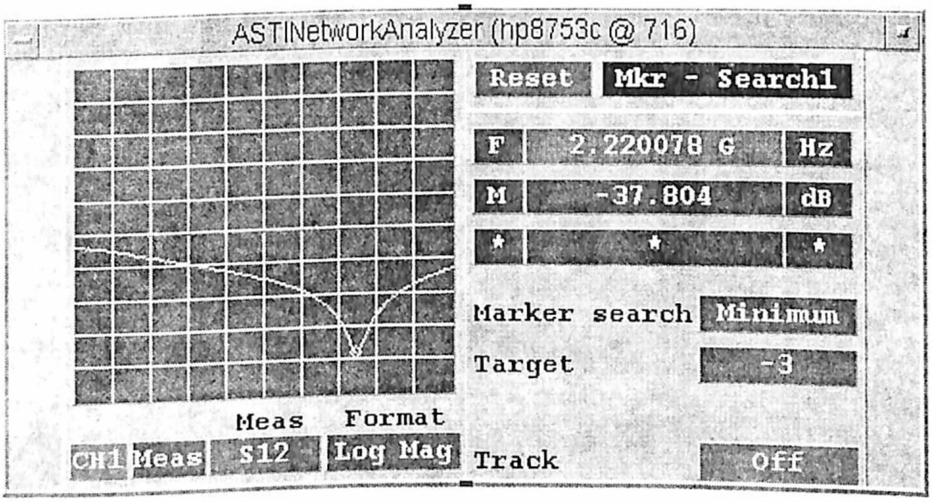
Meas S12

Format Log Mag

CH1 Meas

Track Off

Figure 11. S_{13}


ASTINetworkAnalyzer (hp8753c @ 716)

Reset Mkr - Search1

F 2.220078 G Hz

M -37.804 dB

* * *

Marker search Minimum

Target -3

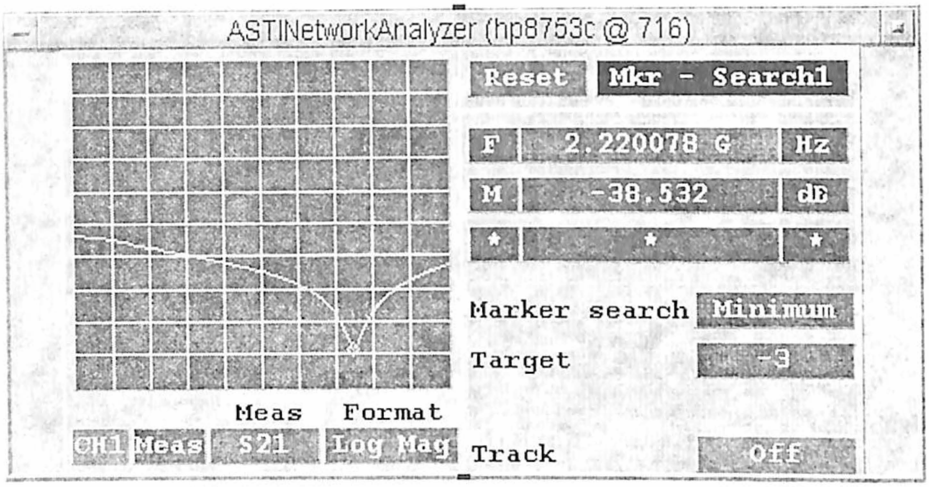
Meas S12

Format Log Mag

CH1 Meas

Track Off

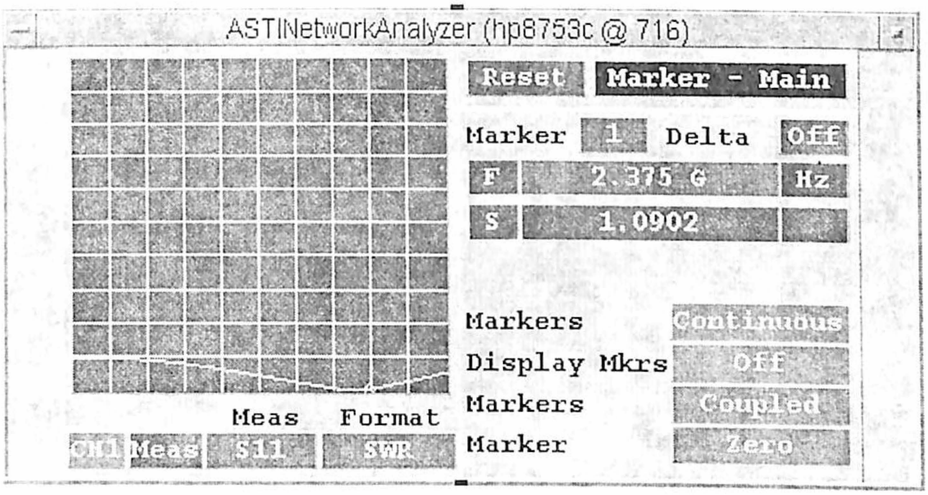
Figure 12. S_{32} minimum



ASTINetworkAnalyzer (hp8753c @ 716)

Reset
Mkr - Search1
F 2.220078 G Hz
M -38.532 dB
* * *
Marker search Minimum
Target -3
Meas Format
CH1 Meas S21 Log Mag
Track Off

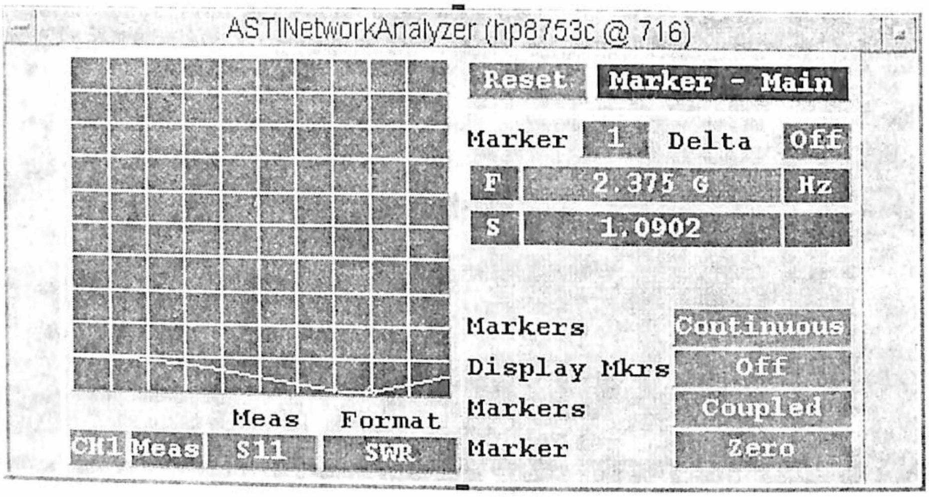
Figure 13. S_{23} minimum



ASTINetworkAnalyzer (hp8753c @ 716)

Reset
Marker - Main
Marker 1 Delta Off
F 2.375 G Hz
S 1.0902
Markers Continuous
Display Mkrs Off
Markers Coupled
Marker Zero
Meas Format
CH1 Meas S11 SWR

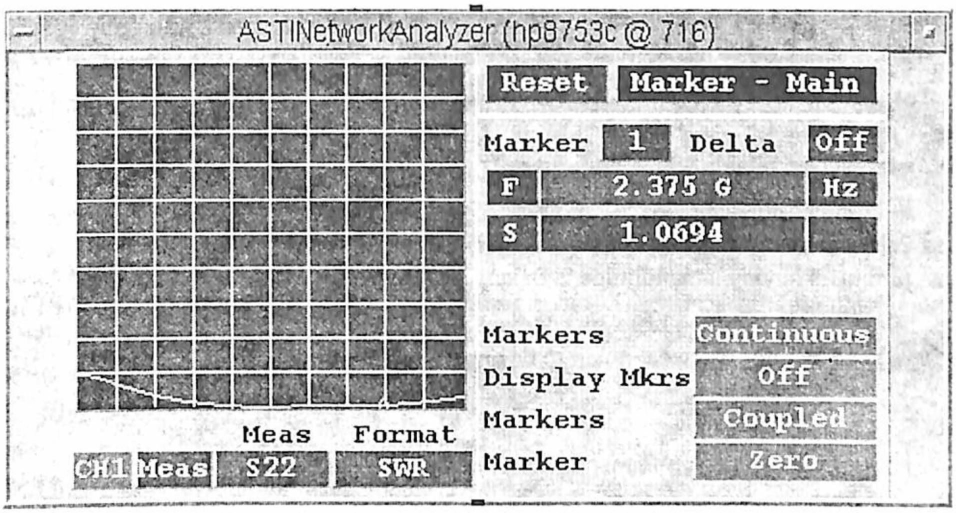
Figure 14. S_{11} SWR



ASTINetworkAnalyzer (hp8753c @ 716)

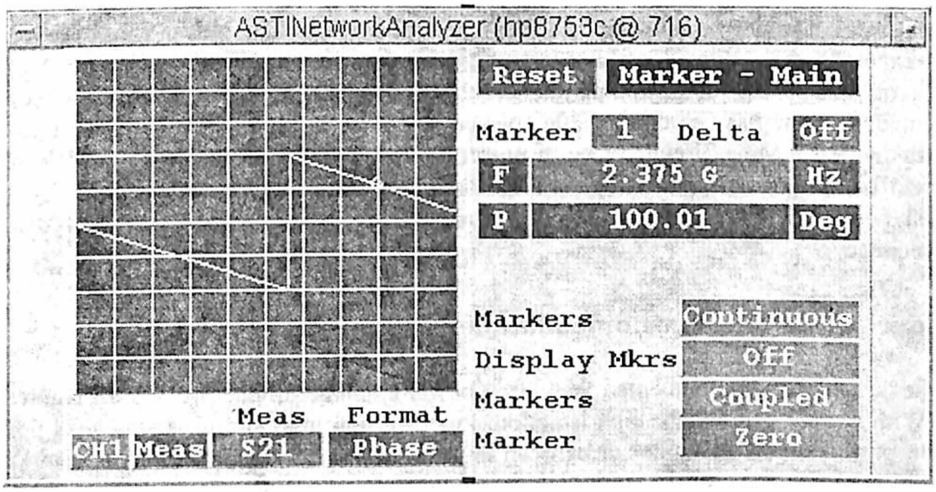
Reset
Marker - Main
Marker 1 Delta Off
F 2.375 G Hz
S 1.0902
Markers Continuous
Display Mkrs Off
Markers Coupled
Marker Zero
Meas Format
CH1 Meas S11 SWR

Figure 15. S_{22} SWR


ASTINetworkAnalyzer (hp8753c @ 716)

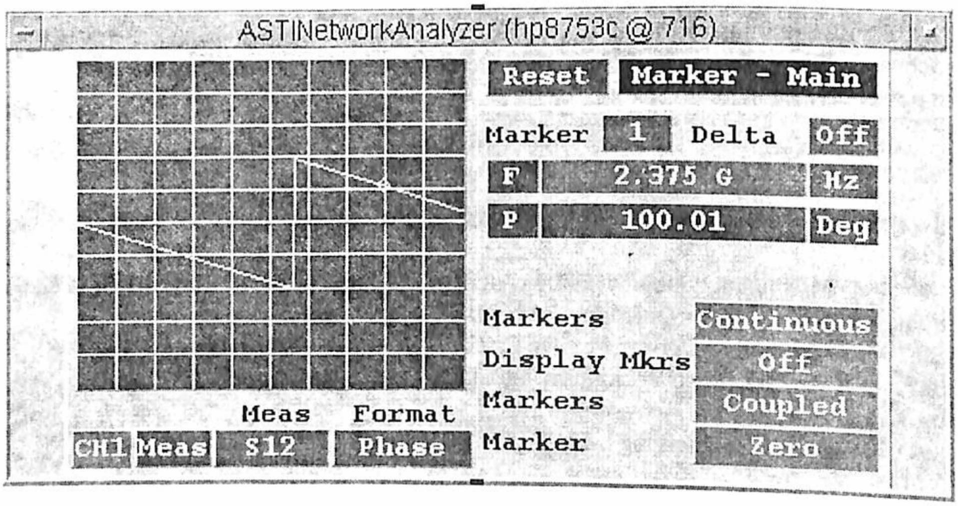
Reset
Marker - Main
Marker 1 Delta Off
F 2.375 G Hz
S 1.0694
Markers Continuous
Display Mkrs Off
Markers Coupled
Marker Zero
Meas Format
CH1 Meas S22 SWR

Figure 16. S_{33} SWR


ASTINetworkAnalyzer (hp8753c @ 716)

Reset
Marker - Main
Marker 1 Delta Off
F 2.375 G Hz
P 100.01 Deg
Markers Continuous
Display Mkrs Off
Markers Coupled
Marker Zero
Meas Format
CH1 Meas S21 Phase

Figure 17. S_{31} phase response


ASTINetworkAnalyzer (hp8753c @ 716)

Reset
Marker - Main
Marker 1 Delta Off
F 2.375 G Hz
P 100.01 Deg
Markers Continuous
Display Mkrs Off
Markers Coupled
Marker Zero
Meas Format
CH1 Meas S12 Phase

Figure 18. S_{21} phase response

Ports 1, 2 and 3 are well matched to the 50-Ω line impedance with VSWR reading of 1.0902, 1.0902 and 1.0694 respectively at 2.375 GHz.

Phase balance was achieved as indicated in Figures 17 to 18 wherein 100.01° phase response for both S_{31} and S_{21}. This is far better than commercially available power splitters/combiners available which introduces 1° to 4° phase unbalance.

Amplitude unbalance is negligible since only 0.0334 dB amplitude difference was obtained relative to S_{21} and S_{31}. This design is comparable with Mini-Circuits' 2 way power splitters/combiners having an amplitude unbalance ranging from 0.1 dB to 0.4 dB.

Likewise, an isolation test was conducted between ports 2 and 3. With port 1 terminated with a 50-Ω load, S_{21} and S_{12} were noted to be approximately -38 dB.

Table 1. Summary of test and measurement results, dB

S_{21}	S_{12}	S_{31}	S_{13}	S_{23}	S_{32}	S_{23}MIN	S_{32}MIN
-3.2314	-3.1967	-3.2648	-3.3023	-27.171	-26.946	-38.532	-37.804

Table 1 summarizes the test and measurement results. The power combiner exhibited very low excess losses. With an intrinsic loss of 3 dB, the constructed power combiner displayed a total loss of 3.2314 dB. Accounting the 0.2 loss contribution of the SMA connectors, the implemented design has a comparable performance with commercially available power combiners/dividers. Mini-Circuits' plug-in power splitters/combiners particularly the MSC 2-11 that works from 5-2000 MHz has a typical insertion loss of 0.6 dB. The loss introduced by the said Wilkinson power divider/combiner design implementation is approximately 0.0314 dB at the design frequency.

VI. Conclusions and Recommendations

The designed and implemented Wilkinson power combiner/divider has a 3 dB bandwidth of 6 GHz. With a wide bandwidth, high isolation, low insertion loss, and phase-matched ports, the Wilkinson power divider/combiner design can be used for broadband applications from DC to 6 GHz. It is the quarter-wave lines that limit the useful bandwidth of the hybrid. Significant improvement in bandwidth can be achieved by using a multi-section design. This problem has been analyzed by Cohn [12] for the case of equal power division. Detailed design information and performance characteristics are given. For example, a four-section hybrid provides excellent performance over a 4-to-1 frequency band, while a seven-section version has a 10 to 1 frequency capability. Significant miniaturization and optimization can be obtained using substrates other than FR4, such as teflon and duroid. Power rating can also be improved above 23 dBm by using medium power surface mount resistors.

References

1. Helszajn, "Microwave Planar Passive Circuits and Filters", Ch. 12, John Wiley and Sons, Inc., (1994).
2. Parad and Moynihan, Split-Tee Power Divider. *IEEE Trans. Microwave Theory and Techniques*, **MTT-13**, 91-95, (January 1965).
3. Rizzi, "Microwave Engineering: Passive Circuits", Prentice Hall International, (1988).
4. Wolff and Kaul, "Microwave Engineering and Systems Applications", Ch. 8, John Wiley and Sons, Inc., (1988).
5. Pozar, "Microwave Engineering", Ch. 8, Addison-Wesley, (1990).

6. Karmel, "Introduction to Electromagnetic and Microwave Engineering", Ch. 13, John Wiley and Sons, Inc., (1998).
7. Gupta, et al, "Microstrip Lines and Slot Lines", Ch. 3, Artech House Inc., (1979).
8. Thomson and Gopinath, Calculation of a Microstrip Discontinuity Inductances, *IEEE Trans.*, **MTT-23**, 648-655, (1975).
9. Silvester and Benedek, "Microstrip Discontinuity Capacitances for Right-angle Bends, T-junctions and Crossings", *IEEE Trans. Microwave Theory and Techniques,* **MTT-23**, 456, (1975).
10. Transmission Line Calculator, Microwave Office 2.66, Applied Wave Research, Inc.
11. Touchstone and Libra, HP EEsof 2.2, RF and Microwave Circuit Design Simulator.
12. Cohn, A Class of Broadband Three-Port TEM-Mode Hybrids, *IEEE Trans. Microwave Theory and Techniques,* **MTT-16**, 110-116, (1968).