# A broadband 180° hybrid ring coupler using a microstrip-to-slotline inverter

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***Abstract* - A new broadband 180° hybrid ring coupler with a Chebyshev return loss response, implemented in microstrip line, and a phase inverter using microstrip-to-slotline transitions, is presented. The transitions were constructed using via short circuits and optimized radial slot stubs. The manufactured prototype was found to operate over a 118% bandwidth in the frequency range 0.72-2.8 GHz.**

***Index Terms*— Mirostrip-to-slotline transitions, Microwave coupler, 180° hybrid, Phase inverter.**

## I. INTRODUCTION

THE 180° hybrid or rat-race coupler is a four-port device that is used in various microwave applications. The device is a power divider that can split the signal at the outputs either in-phase or 180° out of phase depending on the input port being used. These input ports are called the ∑-port (sigma-port) and the Δ-port (delta-port) respectively. Such a standard hybrid coupler can easily be implemented using microstrip lines in a ring like structure. The ∑-port feed-line and the two outputs are separated by λ/4 line sections. The Δ-port has a λ/4 line section to one output port and a 3λ/4 line section to the other output port.

Numerous researchers have published design variations of hybrid couplers to increase the operational bandwidth [1]-[4]. According to Chang et al. [1] a λ/2 section of the 3λ/4 line section can be replaced with an ideal phase inverter to produce a 74% fractional bandwidth coupler. The bandwidth can be increased further (in theory up to 120% with a 15 dB return loss [1]) by adding λ/4 unit elements to each of the ports to achieve a fourth order response. A schematic diagram of such a coupler is shown in figure 1. A prototype was implemented using finite-ground-plane co-planar waveguide (FCPW), and the results showed an excellent bandwidth of 123%. FCPW was used because they could realize a good phase inverter in such a medium, but this increased the manufacturing complexity since it required the use of bonding wires, and it also resulted in high insertion losses [1]. Mo et al. [2] produced a hybrid coupler that was implemented in microstrip line and the inverter was implemented using a microstrip-to-CPW transition.

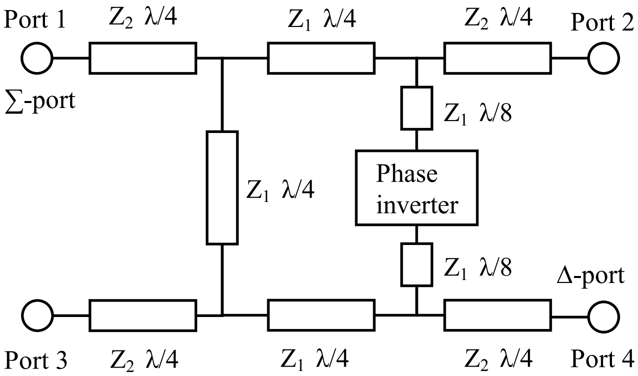


Fig. 1. Schematic of Chebychev response equal-spit rat-race coupler proposed in [1].

A bandwidth of 80% was achieved with acceptable insertion loss [2]. The main problem with this design is that it produced a high phase imbalance of 10º [2]. A hybrid coupler that uses a shorted coupled line section and two shorted quarter-wavelength lines was proposed in [3]. This design achieved a 111% bandwidth, and acceptable insertion loss and phase balance. The manufacturing complexity may make this design undesirable for certain applications. The coupled line inverter was implemented by using two different substrates sandwiched together. A hole was cut away on the substrate which the coupler was etched on. The inverter structure was then placed in the hole and soldered to the coupler structure. A hybrid that was derived from a Wilkinson divider was implemented in [4]. This was achieved by replacing the resistor with a fourth port to effectively incorporate out-of-phase power division functionality. The bandwidth obtained for the ∑-power division and the Δ-power division was 200% and 66% respectively [4]. This significant difference is due to the losses of the microstrip-to-CPW transition that the Δ-port was fed with [4].

In this paper a new broadband 180° hybrid ring coupler, implemented on a single substrate in microstrip line, is presented. A Chebyshev response is achieved using additional unit elements at the ports and proper selection of the characteristic impedances according to the design data in [1]. A microstrip-to-slotline transition [5, 6] was used to implement an inverter. The best results were achieved when a transition was used that terminates the microstrip line with a via short, and radial stubs were found to work better in terms of insertion loss, as also suggested in [6].

## II. HYBRID COUPLER DESIGN

Figure 2 shows the optimized hybrid coupler. The dimensions of the hybrid coupler were optimized in order for the design to yield an optimum result in terms of bandwidth, return loss, amplitude and phase balance at a center frequency of 1.8 GHz. Simulation and optimization was performed using CST Microwave Studio™. Using the Chebyshev response design data in [1], the impedances $Z_1$ and $Z_2$ were chosen as 40.6 Ω and 35 Ω, with an expected bandwidth of 117% and a return loss better than 16 dB (if an ideal inverter is used).

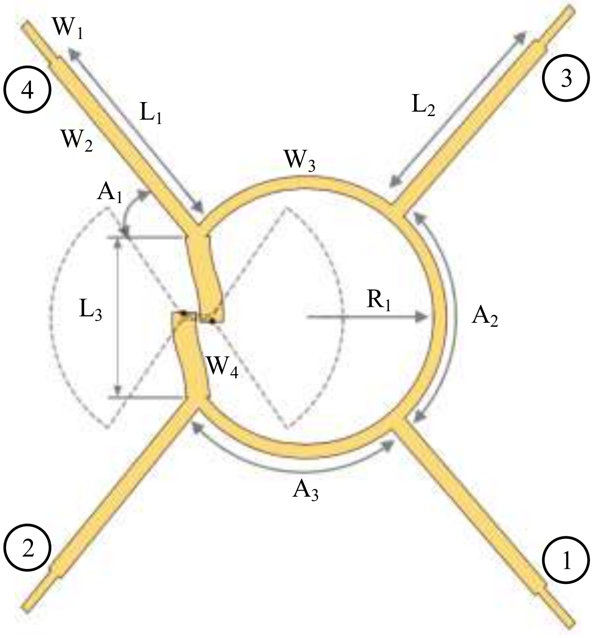


Fig.7 Microstrip section of the hybrid ring coupler. Dimensions of 35 Ω lines (unit: millimeters): $L_1$ = 29.6, $L_2$ = 29.5, $W_2$ = 2. Dimensions of 40.6 Ω lines (unit: millimeters): $L_3$ = 21, $W_3$ = 1.7, $W_4$ = 3.1, $R_1$ = 17.6, other dimensions: $W_1$ = 1.1 mm (50 Ω), $A_1$ = 39.3 º, $A_2$ = 92.9º, $A_3$ = 88.6º. Distance from center of inverter (midpoint of gap) to the center of the unit circle is 14.1 mm. Dashed line indicates slotline section.

## III. INVERTER DESIGN

Figure 3 shows the inverter that was used in this design. The dashed-lines indicate how the microstrip line is connected to the vias. A possible problem with the design of the inverter is that the radial slot stubs can be large relative to the size of the microstrip ring section (see figure 3). Proper choice of substrate can prevent overlap of the slot and microstrip line sections – for this coupler the substrate RT-Duroid™ 5880 ($\varepsilon_r$ = 2.2, h = 0.381 mm) was used. The feed lines of the inverter were meandered by using a cosine function. The slotline length was kept small in order to make the structure realizable and to reduce losses. The inverter as well as its feed lines was designed to be optimally matched to $Z_1$ = 40.6 Ω. Simulation and optimization was done using CST Microwave Studio™. Figures 4 and 5 respectively show the amplitude and phase response of the inverter, including the curved feed line sections. A reflection coefficient better than -10 dB and a transmission coefficient better than -0.5 dB was observed across the entire bandwidth of interest.

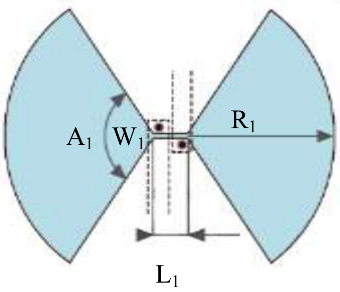


Fig. 3. Slotline section of the microstrip-to-slotline inverter. Dimensions: radius $R_1$ = 17 mm, length $L_1$ = 3.8 mm, slot line width $W_1$= 0.6 mm and angle $A_1$ = 110.6º. Via diameter is 0.4 mm and gap between microstrip-lines (indicated by dashed lines) is 0.8 mm.

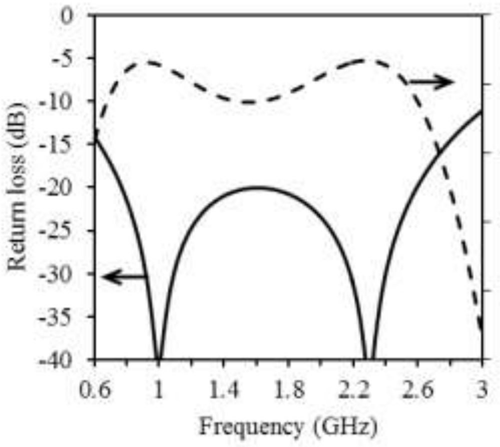


Fig. 4. Simulated S-parameter magnitudes of the inverter section. Ports normalized to 40.6 Ω.

In figure 5 the phase response of a 3λ/4 microstrip line section, designed at a center frequency of 1.8 GHz, is also shown. The microstrip-to-slotline inverter shows a significant improvement. When the response of the inverter section is compared to an ideal phase inverter which is fed with λ/8 lines, the microstrip-to-slotline and the ideal inverter sections have a similar phase response. The difference between these phase responses (between the ideal and the implemented inverter in this paper) is also plotted in figure 5. This difference is a measure of how ideal the designed inverter is. The maximum difference across the 0.6-3.0 GHz band is less than 20º. Even though this is not an ideal inverter, it is relatively easy to implement on a single substrate and was found to work well enough to significantly increase the bandwidth of the hybrid coupler.

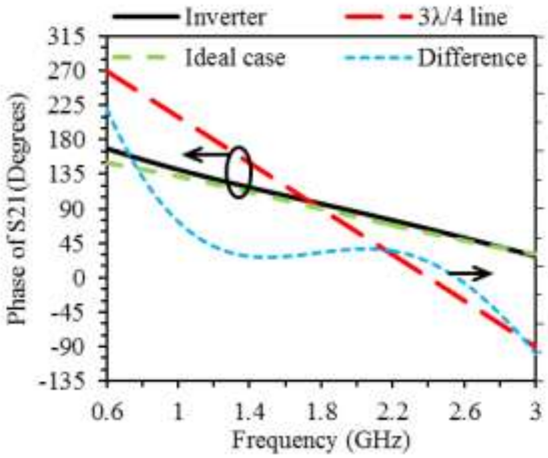


Fig. 5. Simulated phase response of the inverter with λ/8 feed lines, a 3λ/4 line, an ideal inverter with λ/8 feed lines and the phase difference between the designed and the ideal inverter sections.

## IV. SIMULATED RESULTS

The simulated results are shown in figures 6 to 9. We chose to define acceptable bandwidth as a return loss better than 10 dB, and an amplitude and phase imbalance better than 0.5 dB and 5º respectively. A bandwidth of 0.73-2.78 GHz (117%) was achieved. The lower band limit is due to the return loss $S_{44}$. The upper band limit is due to phase imbalance for the Δ-phase difference (port 4), as seen in figure 9. For this 117% bandwidth the isolation was better than 22.4 dB, and the maximum deviation from the ideal 3 dB coupling level was 0.72 dB, as shown in figure 7.

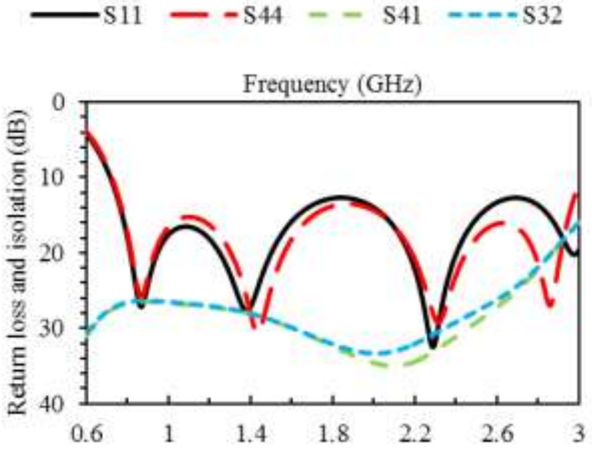


Fig. 6. Simulated return loss and isolation of the hybrid coupler.

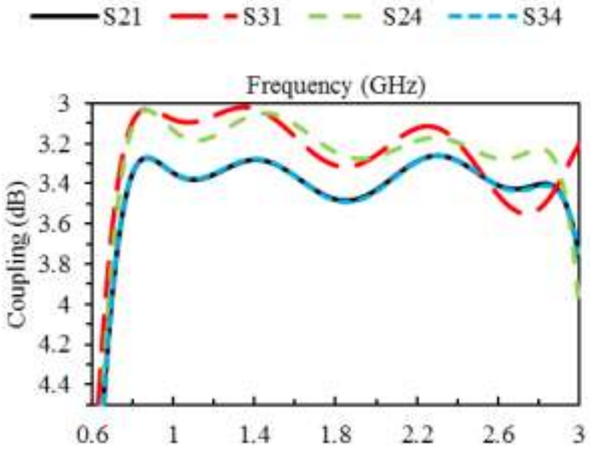


Fig. 7. Simulated coupling of the hybrid coupler.

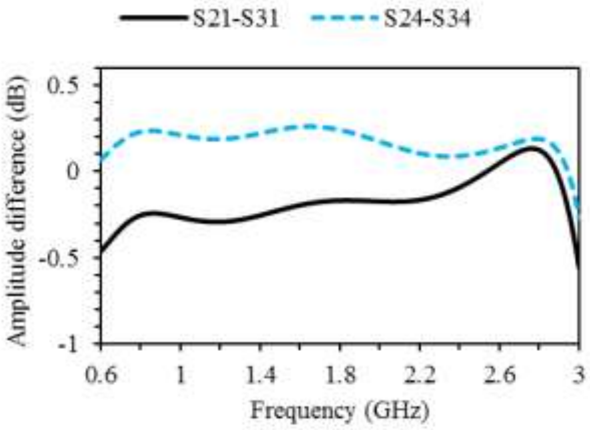


Fig. 8. Simulated amplitude imbalance of the hybrid coupler.

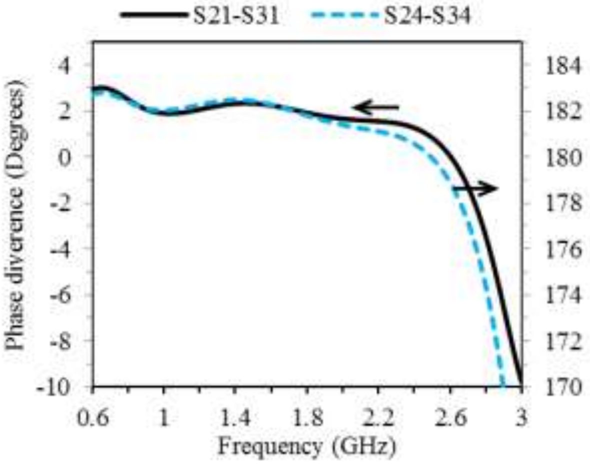
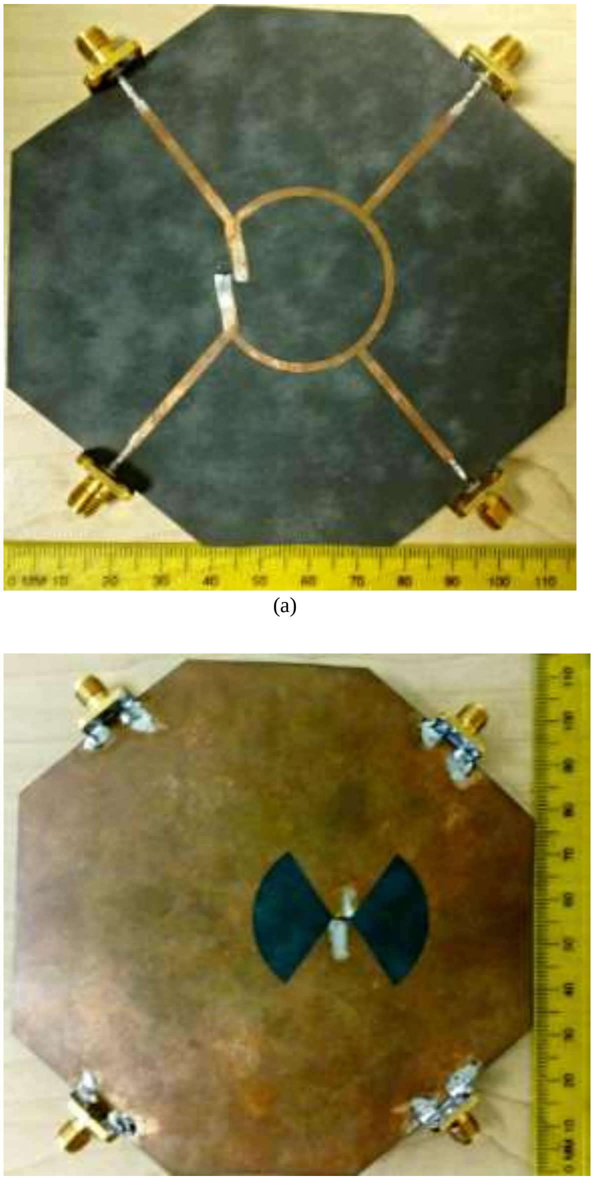


Fig. 9. Simulated phase imbalance of the hybrid coupler.

## V. EXPERIMENTAL RESULTS

The proposed hybrid coupler was manufactured and the measured results are shown in figures 11 to 14. A bandwidth of 0.72-2.8 GHz (118%) was achieved were the return loss is better than 10 dB, and the amplitude and phase imbalance respectively less than 0.5 dB (except for one small spike at 2.7 GHz, see figure 13) and 5º. The lower band limit is due to the return loss $S_{44}$. The upper band limit is due to the phase imbalance for both the Δ and the ∑-phase difference. For this 118% bandwidth the isolation was better than 20 dB. The maximum deviation from the ideal 3 dB coupling value was 1.13 dB, as shown in figure 12.


(a)

(b)

Fig. 10. Manufactured prototype: (a) Top view, (b) Bottom view.

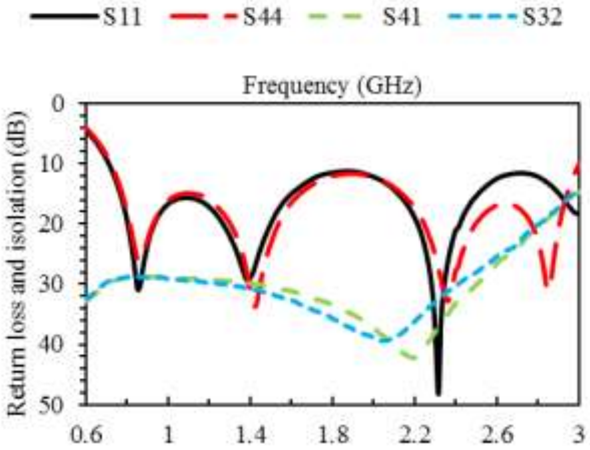


Fig. 11. Measured return loss and isolation of the hybrid coupler.

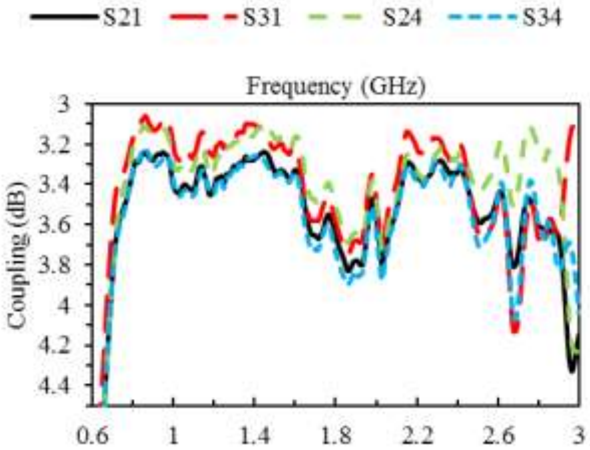


Fig. 12. Measured coupling of the hybrid coupler.

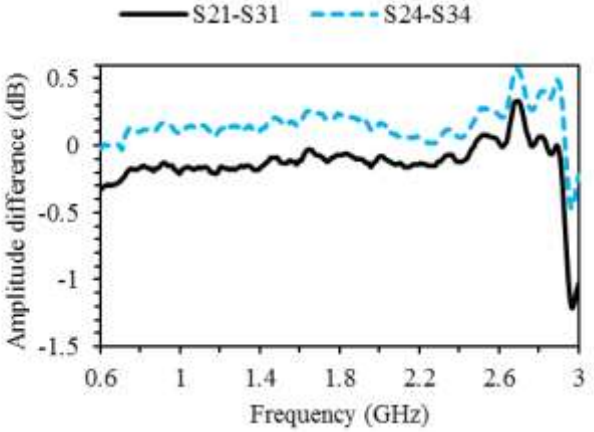


Fig. 13. Measured amplitude imbalance of the hybrid coupler.

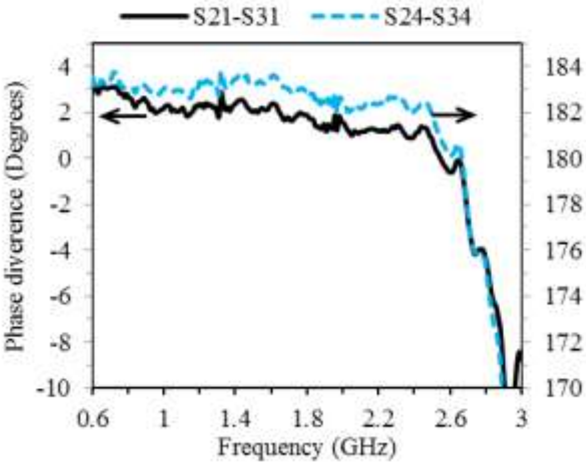


Fig. 14. Measured phase imbalance of the hybrid coupler.

The achieved parameters of the developed hybrid couplers in comparison with the results published elsewhere [1-4] are summarized in Table I.

TABLE I
COMPARISON OF THE ELECTRICAL PARAMETERS OF THE DEVELOPED HYBRID COUPLER WITH SIMILAR DESIGNS

| | **[1]** | **[2]** | **[3]** | **[4]** | **This paper** |
|---|---|---|---|---|---|
| $f_0$ (GHz) | 5 | 2.5 | 1.8 | 1.5 | 1.8 |
| BW (%) | 123 | 80 | 111 | 66 | 118 |
| Return loss (dB) | 14 | 10 | 20 | 8 | 10 |
| Amp. imbalance (dB) | 1 | 0.5 | 0.8 | 0.6 | 0.57* |
| Phase imbalance (deg.) | 5 | 10 | 3 | 2.7 | 5 |
| 3 dB coupling dev. (dB) | 2 | 0.5 | 1.5 | 0.5 | 1.13 |

*This maximum value is due to a spike at 2.7 GHz. The rest of the data values in the defined bandwidth is below 0.5 dB, see figure 13.

## VI. CONCLUSION

A broadband 180º 3 dB hybrid coupler implemented on a single substrate in microstrip line, using microstrip-to-slotline transitions as an inverter, was investigated. The inverter that was designed achieved a fractional bandwidth of 112% with a phase deviation of ±10º. The Chebyshev return loss response was based on work done in [1]. Excellent agreement between simulated and experimental results was achieved. The experimental prototype of the hybrid coupler operates over a 118% bandwidth in the frequency range 0.72-2.8 GHz. The electrical performance is comparable to that of previous designs [1-4], with the advantage that the coupler presented in this paper only requires simple manufacturing techniques and a single layer substrate.

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