Six-port precision directional coupler

T.S. Cooper, G. Baldwin and R. Farrell

A design for a six-port, high phase and amplitude balance, stripline coupler is presented. Both the predicted and the measured performance of a hardware prototype show phase and amplitude balance better than 0.2 dB and 0.9° at the design frequency of 2.46 GHz when fabricated on an FR-4 substrate.

Introduction: During the course of our investigations into phased array calibration the requirement arose for a six-port directional coupler with high coupled-port phase and amplitude balance. This design is based on edge-coupled striplines which have varied little since their conception and characterisation [1, 2]. Since then other coupler configurations have been proposed [3, 4] which do not address the issue of attaining high phase and amplitude balance. Recent work by Kother *et al.* addresses phase and amplitude balance in planar, passive dividers [5]. Previous work by Hines [6] addressed symmetrical couplers, however these do not employ planar construction.

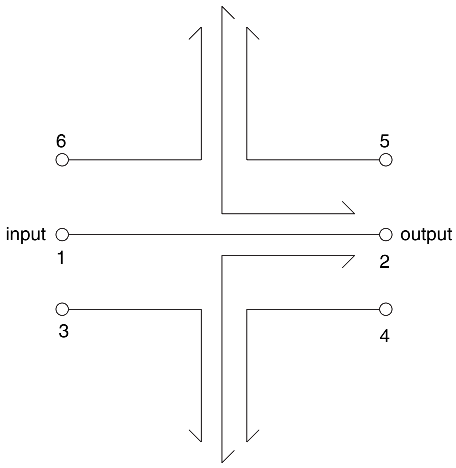

Fig. 1 *Schematic of six-port directional coupler*

Six-port coupler design: In this Letter we introduce a six-port coupler with high amplitude and phase balance between the coupled ports, for use in the ISM-band between 2.4 and 2.5 GHz. The coupler is based on the symmetrical layout of seven edge coupled transmission lines, as in Fig. 1. Contrary to common practice for the design of three-coupled lines [7], the synthesis of each group of coupled lines was based on the simple procedure outlined by Pozar [8] for a single pair of edge-coupled transmission lines. In spite of disregarding other coupling modes the impedance match across the band of interest was adequate ($S11 < -20$ dB and $S33 < -13$ dB at 2.46 GHz) and simplified the synthesis process. Each pair of edge-coupled lines was designed to give a coupling factor of -10 dB. Thus the resultant overall coupling factor from the input (port 1) to each coupled output (ports 3, 4, 5, 6) is -20 dB. The length of the coupled region was tuned to a frequency of 2.46 GHz for ISM-band operation.

Coupler simulation: To confirm the operation of the –20 dB six-port coupler, and assess the attainable port balance under ideal conditions, the design was simulated using ADS Momentum [9]. Fig. 2*a* shows the layout of the stripline coupler. In addition to the edge-coupled lines, through-hole grounded vias were added to screen bordering couplers. Their inclusion improved port balance and allowed significant reduction in coupler size. The separation, *d*, between neighbouring couplers was reduced to 3.5 mm before phase and amplitude balance were adversely affected. The dimensions of the stripline on which the coupler was simulated are shown in Fig. 2*b*, the substrate is FR-4 with $h1 = h2 = 1.6$ mm. All copper layers are 35 µm thick (t).

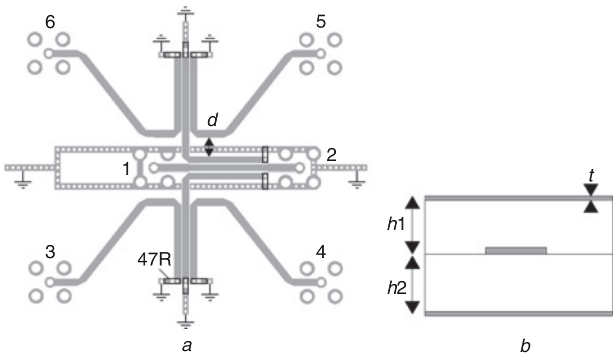

Fig. 2 *Layout of coupler with additional screening structure and detail of stripline layout*

a Layout of coupler with additional screening structure
b Detail of stripline layout

Simulation results: Fig. 3*a* shows the overall response of the coupler; the coupling factor of −21.8 dB and isolation of −51.3 dB are close to their design values. Fig. 3*b* shows the phase imbalance of the forward power coupled to each output port, relative to $S31$; it indicates that the magnitude of the phase imbalance at 2.5 GHz is 0.4°. Note the similarity of error responses for port pairs 4,5 and 3,6 (coinciding on the scale shown in Fig. 3*b*), which is because of their identical geometry. Fig. 3*c* predicts amplitude imbalance of 0.026 dB and shows the same pairing of error responses.

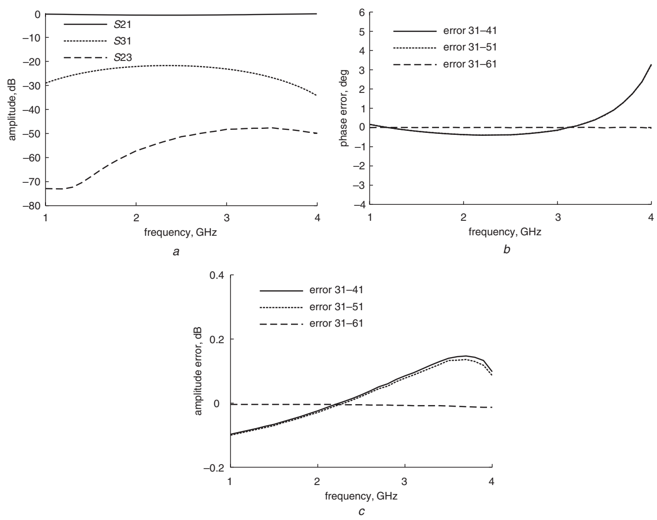

Fig. 3 *Simulated coupler response, phase error and amplitude error*

a Simulated coupler response
b Simulated phase error
c Simulated amplitude error

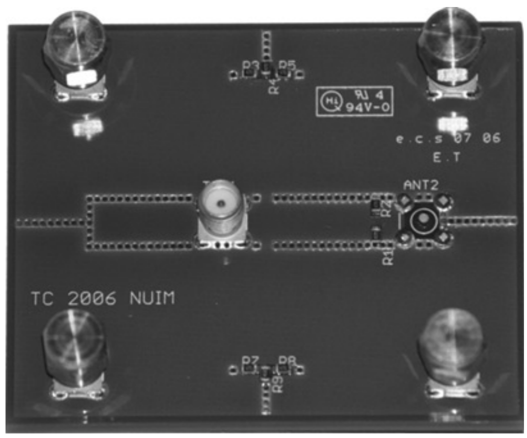

Fig. 4 *Image of prototype stripline coupler*

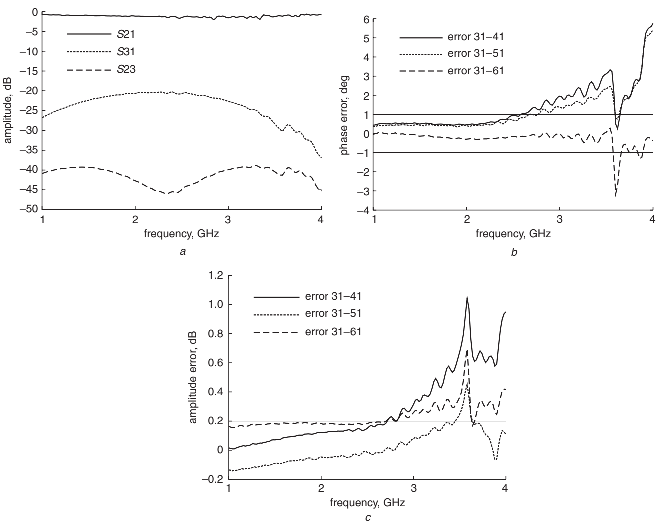

Fig. 5 *Measured coupler response, phase error and amplitude error*

a Measured coupler response
b Measured phase error
c Measured amplitude error

Prototype coupler testing: To substantiate simulation predictions a prototype −20 dB coupler was produced on a three-layer FR-4 substrate (see Fig. 2*b*). The prototype, Fig. 4, was manufactured by ECS circuits [10] and comprised one double-sided FR-4 PCB (forming *h*2) with a further pre-impregnated substrate layer (*h*1) above. Permanent terminations were made through blind vias to 47 Ω 5% tolerance resistors and any ports unused during testing were matched with 50 Ω SMA terminations. The coupler was tested using a Rhode & Schwarz ZVB 20 [11]. Measurement results are shown in Fig. 5. They were made with input power of 0 dBm and 10 data point averaging. This setup yielded measurement accuracy of approximately 0.042 dB and 0.05° at the design frequency. Fig. 5*a* shows important coupler responses. The insertion loss (*S*21) of −1.6 dB was higher than expected, so in future design iterations weaker first stage coupling to reduce this loss will be considered. The designed coupling factor of −20.8 dB was achieved, varying little from simulation, and isolation of −45.7 dB was observed, 5.6 dB lower than predicted. The resultant phase error is shown in Fig. 5*b*. Its maximum value is 0.87°, roughly double that predicted at 2.46 GHz. As a visual aid, in Fig. 5*b*, horizontal lines indicate 1° of peak phase error. The peak measured amplitude error is shown in Fig. 5*c*; similar lines indicate 0.2 dB of peak error. At our design frequency the measured amplitude error was almost an order of magnitude higher than simulation at 0.18 dB. While both error plots have additional features, most likely due to the FR-4 substrate material, both have similar underlying characteristics to simulation, including pairing of error responses.

Conclusion: A simple design for a six-port, precision phase and amplitude coupler is presented. Measured results indicate that at and below the design frequency of 2.46 GHz, balance of better than 0.2 dB and 0.9° is attainable. Future study will investigate lower cost embodiments using standard multi-layer PCB build geometries (i.e. asymmetrical stripline) and further techniques aimed at increasing bandwidth and improving balance of the coupler.

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