Ka-Band Surface-Mount Directional Coupler Fabricated using Micro-Rectangular Coaxial Transmission Lines

Kenneth Vanhille*, Jean-Marc Rollin*, Sebastien Rondineau†, John O'Brien†, Joseph Wood‡, Sanjay Raman‡, and Zoya Popovic†

*Rohm and Haas Electronic Materials LLC, Blacksburg, VA, 24060, USA
†Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO, 80309, USA
‡Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, 24061, USA

***Abstract* — 2.5-dimensional, 10-dB and 20-dB directional couplers, are designed and fabricated using air-core rectangular coaxial transmission lines. The couplers are both smaller than 1.8 by 4.2mm^2 with probing points. The measured performance of the coupler is in agreement with full-wave simulations. The components are designed such that probing or flip-chip attachment can be done with the same structures. A flip-chip transition from rectangular coax to traditional co-planar waveguide is also presented.**

***Index Terms* — Coupled transmission lines, coaxial couplers, coaxial transmission line, and photolithography.**

I. Introduction

Directional couplers at microwave and millimeter-wave frequencies can have several topologies such as branch-line couplers, as well as coupled-line couplers, including Lange and overlay couplers. A comprehensive study of both symmetric and asymmetric multilayer directional couplers at frequencies below 8GHz is given in [1].

Air-core or air-filled microfabricated rectangular coaxial transmission lines exhibit several benefits in comparison to traditional planar transmission lines such as microstrip and coplanar waveguide (CPW). Rectangular coaxial transmission lines are broadband, have dominant TEM operation to 450 GHz (for a 250 by 250μm^2 inner dimension of the outer conductor), exhibit low loss, and have high isolation because of the natural shielding of the outer conductor [2]. Rectangular coaxial branch-line couplers in the Ka- and V-bands have been presented in a nickel fabrication process previously, [3] and [4].

A microfabrication process using copper and including a periodic dielectric support for the center conductor has been developed by Rohm and Haas Electronic Materials, LLC and a brief description of the fabrication process and results for a few micro-coaxial devices are presented in [5]. Balanced branch line couplers using copper have been presented in [6]. The present work demonstrates the design, fabrication and measurement of 10-dB and 20-dB directional couplers with a center frequency of operation at 26GHz. An SEM of a 10-dB coupler is shown in Fig. 1 with the mechanical model shown as a comparison. These couplers are compatible with other millimeter-wave components using the same fabrication process. These devices can either be measured using GSG probes, or they can be flip-chip attached using fluxless solder technology or conductive epoxy. Devices fabricated using the PolyStrata™ process can be detached from the original silicon carrier before being assembled on a different carrier. A 1-cm rectangular transmission line is flip-chip attached using conductive epoxy to a coplanar waveguide transition and RF measurements are shown to agree well with simulation.

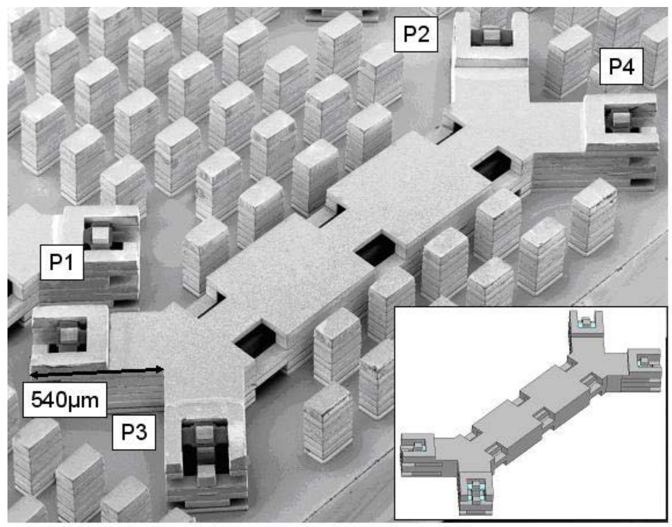

Fig. 1. An SEM image of a 10-dB directional coupler fabricated using micro-rectangular coax designed for operation centered around 26 GHz. The naming convention for the ports is labeled and an insert of the model used for simulating the design is shown in the bottom right corner.

II. 2-D Design

For the desired coupling, high isolation, and a well-matched input, an accurate calculation of the even- and odd-mode impedances for different dimensions of the coupled transmission line is required. Classical directional couplers are implemented using stripline or microstrip with the signal conductors lying in the same plane; however, other coupled transmission line topologies exist. Several directional couplers with both tight and low coupling levels using multi-layer structures are presented in [7]. In addition, broadside couplers on gallium arsenide have also been reported with better than

20-dB isolation from 20 to 40GHz [8]. In this paper, the signal conductors lie in the same plane, however when the fabrication uses more layers, tighter coupling can be achieved using other configurations [9]. Several methods have been used to compute the even- and odd-mode impedances in the past. A numerical implementation of conformal mapping has been used to design directional couplers with multiple conductors, giving accurate results [10]; however, symmetry is necessary in one plane. Because some line cross sections that have been fabricated--though are not presented here--do not fit these constraints, the characteristic impedances for different cross sections is calculated using a more general method.

COMSOL Multiphysics™ is employed to solve for the electric potential of the cross-section with Laplace's equation using the 2-D finite element method. The characteristic impedances are found using $Z_0^e = 1/cC_e$ and $Z_0^o = 1/cC_o$, where C_e and C_o are the calculated even- and odd-mode capacitances and c is the speed of light. The impedances for different values of w and g (from Fig. 2(a)) that are possible to fabricate and potentially useful are shown for a 10-dB coupler in Fig. 2(b) and for a 20-dB coupler in Fig. 2(c). With the different impedance combinations that are possible, it is necessary to choose a combination that is matched to 50Ω and provides the desired coupling. Lines denoting these characteristics are indicated in Fig. 2, and their crossing point gives the starting values for the 3-D design. The 50-Ω match line is calculated from the equation

$$Z_m = \sqrt{Z_0^e Z_0^o} \quad (1)$$

and the 3-dB coupling line is calculated using

$$Z_0^e = Z_m \sqrt{\frac{1+C}{1-C}} \quad (2)$$

$$Z_0^o = Z_m \sqrt{\frac{1-C}{1+C}} \quad (3)$$

where C is the voltage coupling value. The 'O' on the graph indicates the value that is chosen after the 3-D modeling. For the 10-dB coupler, g=48μm w=105μm, and w_o=100μm. For the 20-dB coupler, g=120μm w=95μm, and w_o=50μm. These are quite close to what was predicted using 2-D methods, however slight differences exist because of the parasitic reactances associated with feeding the coupled-line section.

III. 3-D Design and Measurement Results

After the cross section has been calculated, the results are used to design the directional coupler. The full model is simulated using Ansoft HFSS™ and fine-tuning of the design is performed. The electromagnetic effects of release holes, used to remove the sacrificial photoresist from the structure, and periodic support straps for the center conductor

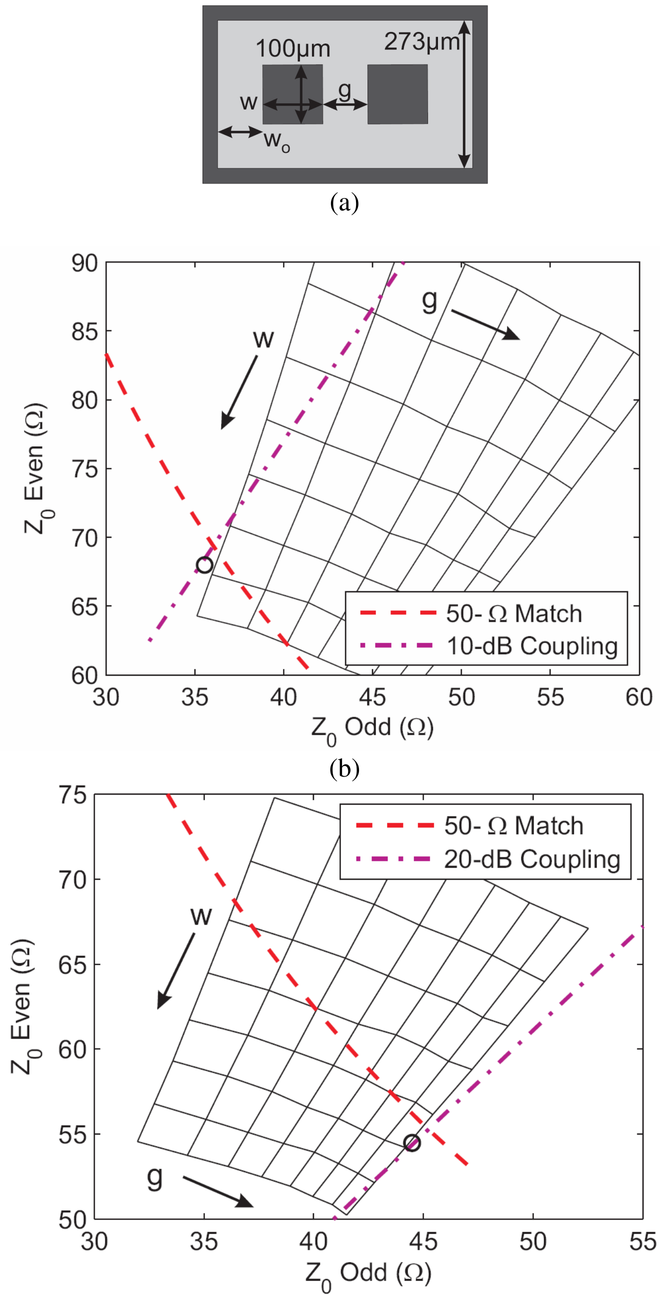

Fig. 2. The calculated even- and odd-mode impedances for the directional couplers fabricated using coupled lines. (a) Sketch of the general cross section of the coupled transmission lines. (b) Each negatively-sloped contour represents an increase in w of 5μm, with a starting value of 75μm. Each positively-sloped contour represents a 10μm increase in g, with a starting value of 50μm. For this case, w_o is 100μm. (c) Each negatively-sloped contour represents an increase in w of 5 μm, with an starting value of 70μm. Each positively-sloped contour represents a 10μm increase in g, with a starting value of 50μm. w_o is 50μm for this case.

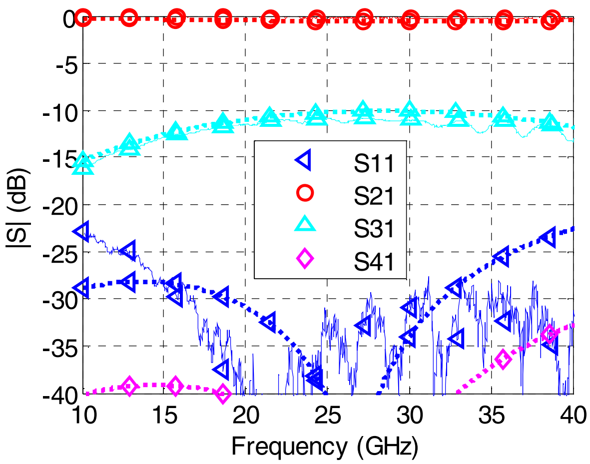

Fig. 4. Simulated (dotted) versus measured (solid) S parameters for a 10-dB coupled-line directional coupler designed for operation centered around 26 GHz.

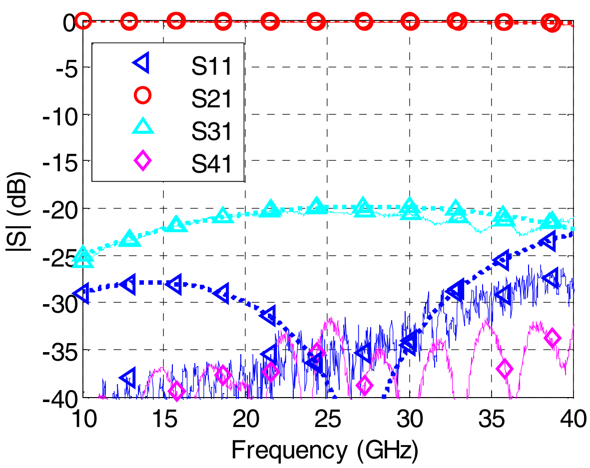

Fig. 5. Simulated (dotted) versus measured (solid) S parameters for a 20-dB coupled-line directional coupler designed for operation centered around 26 GHz.

are treated in the full-wave model. An SEM image of the fabricated 10-dB coupler is shown in Fig. 1.

Fig. 4 shows a comparison of the measured and simulated values for the frequency response of the S parameters of the 10-dB coupler. The coupled port has a coupling level of 11dB ±0.25dB from 22GHz to 30GHz. The phase difference between the coupled port and the through port is 85° ±5° over the same bandwidth. Fig. 5 shows the same type of graph for the 20-dB coupler. The coupled port has a coupling level of 20.5dB ±0.5dB from 22GHz to 30GHz. The phase difference between the coupled port and the through port is 88° ±4° over the same bandwidth. The measurements of the couplers are done on a Cascade Microtech Summit 9000 probe station with an Agilent two-port E8364B network analyzer. A TRL calibration is performed on wafer. A series of six two-port measurements are made between alternating ports with the other ports terminated with broadband loads attached using microwave probes. The broadband loads are characterized by making two one-port measurements of a TRL thru structure with each broadband load attached to one end. Using these data sets, the full four-port S parameters are derived using the multi-port algorithm outlined in [11]. It is believed that measurements using a four-port network analyzer would provide measurement results that agree more closely with simulation, as has been seen in [6]. The directivity of the 20-dB directional coupler is measured to be less than 10dB near 35 GHz, and it is believed that this is due to our inability in practice to use the same terminations at each of the output ports of all of the measurements.

IV. Flip-Chipped Microcoax Component

The device shown in Fig.1 is connected to test equipment via 3-D launches for standard 150-um pitch CPW probes, as discussed in [9]. The PolyStrata lines, however, do not need to stay on the mother substrate – they can be chemically detached from the substrate and hybridly integrated with other components and can be mounted on other substrates. Therefore, the probing interconnect of the devices from Fig.1 has been designed to allow flip-chip mounting of these components in other circuits.

To demonstrate the feasibility of hybrid integration of PolyStrata lines, 15-µm-thick conductive epoxy has been deposited on 100-µm pads on a PolyStrata device. The 1-cm rectangular coaxial line was then flip-chip attached to a pair of 5.85-mm CPW transmission lines on a 550-µm-thick high-resistivity silicon substrate. An example of a completed assembly is shown in Fig.6.

Fig. 6. Photograph of a 1-cm micro-rectangular coaxial transmission line flip-chipped onto CPW on 550-µm-thick high-resistivity silicon. The length of CPW on each side of the coaxial element is 5.85mm.

The assembled part was measured on a microwave probe station using an Anritsu 37369 VNA. The calibration was done using SOLT on an alumina external calibration substrate. Fig. 7 shows the measurement results compared to a full-wave simulation of the measurement setup. The simulation assumed lossless silicon, so an S21 measurement of 11.7mm of CPW on silicon is also shown to give a baseline comparison for the losses induced by the CPW on silicon. The two CPW-to-coax transitions plus 1-cm of transmission line add roughly 1dB to the losses of the CPW at 30GHz. The percm loss of the 250x250μm^2 coaxial line at 30GHz is 0.2dB/cm—meaning each transition adds 0.4dB of loss.

Although the reported flip-chip device of this example is a transmission line, other micro-coaxial components such as couplers, filters, and balun transformers can be flip-chip attached in a similar fashion. The technology is also compatible with thin film solder technology such as AuSn or SnAgCu which can be integrated at the wafer level.

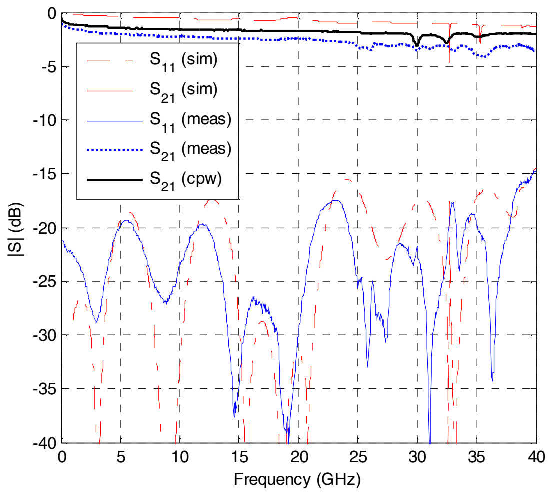

Fig. 7. A comparison of measurement and simulation for the 1-cm rectangular coaxial transmission line flip-chip attached to a CPW transition on silicon. S21 of a 11.7-mm length of CPW on silicon represents the loss from the CPW transitions to the probe pads.

V. Conclusion

10-dB and 20-dB directional couplers have been designed, fabricated, and measured using the PolyStrata™ process and are completely compatible with other devices fabricated using this process. These design techniques can be extended to higher coupling ratios (3-dB and greater) using multiple signal conductors when more strata are used in the fabrication process. These coupler does not suffer from the complications of imbalanced even- and odd-mode phase velocities that have been common in the past with Lange couplers because the coupled section of the lines are homogeneously air-loaded.

The directional couplers or other components can be flip-chip attached for use in other circuits. To the best of the authors' knowledge, the presented flip-chip attachment of a rectangular coaxial transmission line to CPW on silicon is the first reported example of flip-chip attachment of a micro-rectangular coaxial device. Although the losses from the transition are higher than expected, this is partially due to the conductivity of the conductive epoxy. To solve this problem, integrated AuSn solder is being developed to allow low-resistivity attachment. The simulated performance up to 110GHz shows low insertion loss using solder attachment. This provides the possibility to integrate air-filled microcoaxial components into other circuit technologies where loss, isolation, or other performance parameters may limit the capability of classical substrate technologies.

Acknowledgment

The authors would like to thank Mr. David Sherrer and the Rohm and Haas Microfabrication Team, Blacksburg, VA; and Prof. Dejan Filipovic of the University of Colorado, Boulder, for helpful technical input.

References

[1] K. Sachse and A. Sawicki, "Quasi-ideal multilayer two- and three-strip directional couplers for monolithic and hybrid MICs," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 9, pp. 2339–2345, Sept. 1999.

[2] M. Lukic, S. Rondineau, Z. Popovic, and D. Filipovic, "Modeling of realistic rectangular μ-coaxial lines," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 5, pp. 2068–2076, May 2006.

[3] R. T. Chen, E. R. Brown, and R. S. Singh, "A compact 30-GHz low loss balanced hybrid coupler fabricated using micromachined integrated coax," in *2004 Proc. IEEE Radio and Wireless Conf.*, Atlanta, GA, Sept. 2004, pp. 227–230.

[4] J. Reid and R.Webster, "A 60 GHz branch line coupler fabricated using integrated rectangular coaxial lines," in *2004 Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, June 2004, pp. 441–444.

[5] D. S. Filipovic, Z. Popovic, K. Vanhille, M. Lukic, S. Rondineau, M. Buck, G. Potvin, D. Fontaine, C. Nichols, D. Sherrer, S. Zhou, W. Houck, D. Fleming, E. Daniel, W. Wilkins, V. Sokolov, and J. Evans, "Modeling, design, fabrication, and performance of rectangular μ-coaxial lines and components," in *2006 Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, San Francisco, CA, U.S.A., June 2006, pp. 1393–1396.

[6] K. Vanhille, D. Filipovic, C. Nichols, D. Fontaine, W. Wilkins, E. Daniel, and Z. Popovic, "Balanced low-loss Ka-band μ-coaxial hybrids," in *2007 Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, Honolulu, HI, U.S.A., June 2007.

[7] C. Person, L. Carre, E. Rius, J. P. Coupez, and S. Toutain, "Original techniques for designing wideband 3D integrated couplers," in *1998 Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, Baltimore, MD, June 1998, pp. 119–122.

[8] S.-F. Chang, J.-L. Chen, W.-L. Chen, and H.-P. Hwang, "A new MMIC broadside coupler using an array of air-bridges for directivity enhancement," *IEEE Microwave Wireless Compon. Lett.*, vol. 14, no. 6, pp. 304–306, June 2004.

[9] K. Vanhille, "Design and characterization of microfabricated three-dimensional millimeter-wave components," Ph.D. Dissertation, University of Colorado, Boulder, CO, USA, 2007.

[10] V. Teppati, M. Goano, and A. Ferrero, "Conformal-mapping design tools for coaxial couplers with complex cross section," *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 10, pp. 2339–2345, Oct. 2002.

[11] J. C. Tippet and R. A. Speciale, "A rigorous technique for measuring the scattering matrix of a multi-port device with a two-port network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 661-666, May 1982.