A Broadband Surface-Micromachined 15-45 GHz Microstrip Coupler

Bo Pan, Y. Yoon, Y.Z. Zhao, J. Papapolymerou, M. M Tentzeris and M. Allen

School of Electrical and Computer Engineering, Georgia Institute of Technology,

Atlanta, GA, 30332, USA

Abstract — **A broadband elevated microstrip coupler has been designed and implemented on the soda-lime glass with surface micromachining technology. The coupler is elevated by 200 µm and fed by a combination of epoxy-core metal post and coplanar waveguide, which helps eliminate the conventional air/dielectric interface problems. By this method, frequency dispersion and attenuation due to the substrate can be effectively reduced. A 10 dB return loss and a 12.5 dB coupling is measured in our experiment over 15-45 GHz. The proposed structure can be implemented on very lossy substrates, such as standard CMOS substrate and thus can be applied into the integration of high performance RF components with digital or optical functions/subsystems on low-cost low-resistivity silicon wafers.**

Index Terms — **Surface micromachining, microstrip directional coupler, broadband coupler, epoxy core conductor**

I. Introduction

Emerging wireless communication and sensor applications in the RF/Microwave/millimeter wave regimes require a high degree of system-level integration. All different function (digital, RF, optical, etc) modules, thus, need to be implemented on a single type of wafer and package [1]. There is a trend of integrating RF/microwave integrated circuits onto low-cost low-resistivity silicon using standard CMOS production processes [2] [3]. The resistivity of the doped silicon substrate used in CMOS technology ranges from 0.01~20 Ω·cm. This type of substrate demonstrates a very high loss tangent which is unfavorable for RF applications.

Considering fabricating a single-section microstrip directional coupler on lossy substrates such as standard CMOS substrate, the loss of the substrate and the non-TEM nature of the propagating wave along the air/dielectric interface will set limitations to the coupler's performance in several aspects. The coupling bandwidth and the isolation are limited by the difference of different mode phase velocities caused by the air/dielectric interface [4]. And, most important of all, high substrate loss will severely degrade the coupler performance. Various methods have been investigated to improve the performance by compensating non-TEM mode transmission and eliminating substrate losses. [5] uses multi-section couplers to get wider bandwidth but it increases the total size. A multi-layer overlapped structure [6] was designed to compensate non-TEM mode transmission, but the loss of the substrate is a drawback since the line is embedded in the substrate. A coplanar waveguide coupler can be used [7] to get near-identical dielectric loading for both even and odd modes, but it still can not completely eliminate the substrate loss. Other technologies include the deposition of low loss thin film polyimide on top of the silicon substrate [2][3] to decrease the loss associated with the substrate.

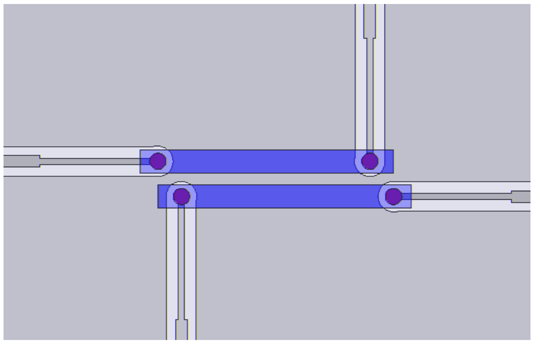
In this paper, based on a metal-coated epoxy core MEMS structure we have developed earlier [8], a novel method is proposed to diminish both loss generated by the substrate and non-TEM mode wave transmission. The coupler is elevated to a height of several hundred microns by supporting posts. The structure is fed using a vertical conductor-coated epoxy core probe that is connected with coplanar waveguide on the top surface of the lossy substrate. The substrate is, thus, covered by a ground metal on top and electromagnetic field of the coupler itself will not leak into the lossy substrate. The elimination of the dielectric/air interface helps reduce the mode dispersion and associated problems such as poor isolation. The coplanar waveguide feeding scheme is preferred since it is compatible with the assembly of MMIC surface mount active devices. Thick metal electroplating for the microstrip coupler is used to enhance coupling by introducing vertical coupling from the side walls.

In our work, a 200 µm elevated microstrip directional coupler prototype is fabricated on the soda-lime glass that has an ε_r of 7.75. It demonstrates 10 dB return loss and 12.5 dB coupling over 15-45 GHz for just a single section.

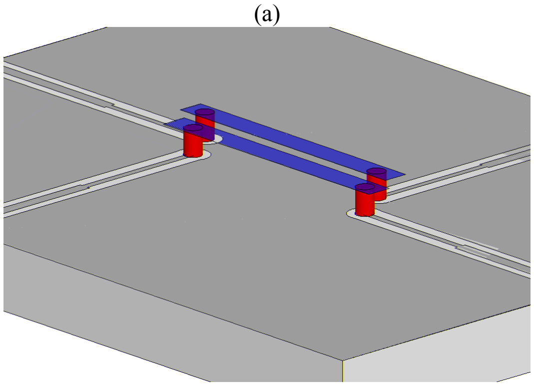
This scheme is proposed as a unique method to develop high performance RF front-end components on lossy substrates since the fabrication is completely compatible with standard CMOS substrates. This helps integrating RF components with digital or optical functions in a single package.

II. Detailed Design and Simulation Results

The configuration of the proposed elevated microstrip coupler is shown in Fig. 1(a)(b). The elevated microstrip is supported and fed at the end by the metal-coated epoxy core probe that we have previously developed [8]. The metal probe is directly connected with a quarter wavelength CPW impedance transformer in order to convert input impedance of the coupler to standard 50 Ω at the input ports. The feeding CPW lines and the coupler share the ground plane in a simple and natural way which makes air the only dielectric between the coupler and the ground plane. This helps eliminate the loss generated in the lossy substrate, as well as the dispersion caused by the air/dielectric interface. Fig. 2 shows how the different air/dielectric interfaces affect the frequency dispersion for even/odd mode of transmission for several materials. The ratio of even-mode wavelength to odd-mode wavelength among air (ε_r=1), LCP (ε_r=3.1), LTCC (ε_r=5.4) and Silicon (ε_r=11.9) substrates is compared in Fig. 2. Apparently, there is no frequency dispersion for air filling, which is our proposed structure.



(a)



(b)

Fig. 1. (a) Top view of the coupler with integrated impedance transformer (b) 3-D view of the elevated coupler

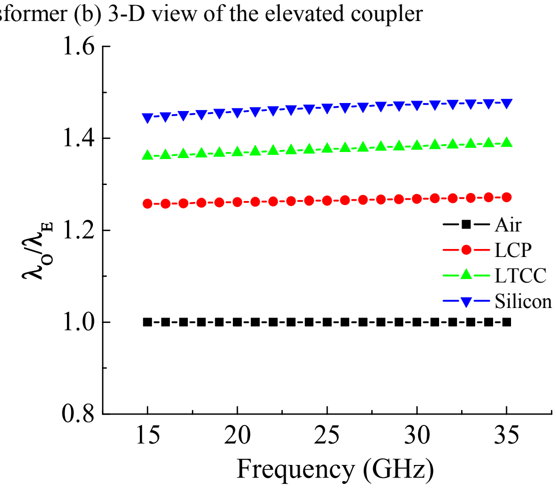


Fig. 2. Even/odd mode wavelength ratio vs. frequency for air, LCP, LTCC and silicon

There are several variables that need optimization in the coupler design: *w*- the width of the elevated microstrip line, *s*- the gap between the two lines, *H*- the height of the elevation and *T*- the metal thickness of the coupler. The following equations guide the optimization of *w* and *s*:

$$C_e = C_{11} = C_{22}\,,\ C_o = C_{11} + 2C_{12} = C_{22} + 2C_{12}$$

$$Z_{0e} = \frac{1}{\upsilon C_e}, Z_{0o} = \frac{1}{\upsilon C_o}$$

where C_e (also C_{11},C_{22}) is the even-mode capacitance which is determined mainly by the separation from the ground, C_o is the odd- mode line capacitance which is determined by both the separation from the ground and the gap between the two lines. Furthermore, the *w* and *s* will affect *Ze* and *Zo*. As a simple rule, the narrower the lines, the higher *Ze*, the smaller the gap, the lower *Zo* can be achieved.

Also, if the coupler is terminated with an impedance of $Z_0 = \sqrt{Z_{0e}Z_{0o}}$, the input impedance will also be

$$Z_{in} = Z_0$$

In our design, a 200 µm width and a 100 µm gap lead to a *Ze* of 150 Ω and *Zo* of 75 Ω, and we need a Z_0 of 108 Ω. It is true that a wider line width *w* and a narrower gap *s* can achieve lower input impedance. However, a tradeoff should be made to try to avoid infeasible gap values or line widths. Large line widths introduce more parasitic radiation from the edge of the line. Narrow line gaps are hard to implement in our fabrication.

Another important design parameter is the thickness of the elevated microstrip line. As simulated results show in Fig. 3, the thicker the metal, the stronger the coupling we can achieve. Thick metal makes the vertical wall coupling possible (the vertical walls functions as a parallel-plate capacitor). A thicker metal also results in a slight reduced attenuation as shown in Fig. 3.

The final variable is the height of the elevation. The higher the structure, the higher parasitic radiation is generated. However, elevating the coupler to a height up to a few hundred microns does not introduce a significant radiation loss, while it makes it possible to electroplate several tens of microns of microstrip line which is beneficial to the vertical coupling. Compared to the air-bridges used in MEMS switches, the use of a metal post makes it possible to vary the height of the structure from several tens of microns up to one millimeter. This will introduce another independent variable for designing.

The final optimized values of the coupler are summarized in Table 1.

Table 1. Dimensions of the prototype geometry

	w	*s*	*T*	*H*
value (µm)	200	100	10	200

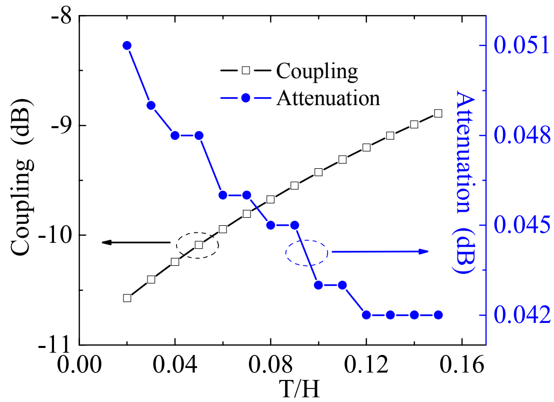


Fig. 3. Coupling and line attenuation vs. normalized metal thickness (the metal thickness *T* is normalized by the elevation *H*)

The structure is simulated using the FEM based Ansoft HFSS V9.1 software tool. The simulation results showing through, coupling, matching, and isolation performance of the coupler are shown below.

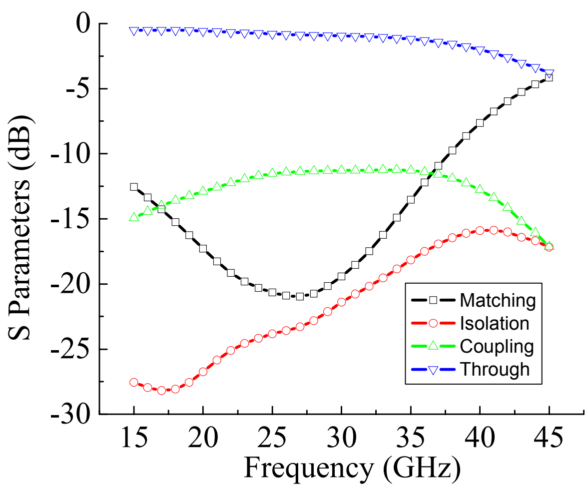


Fig. 4. Simulated coupler performance

From the simulation, an 11 dB coupling, a 10 dB matching for all ports and a 15dB isolation for isolated ports have been observed over 15- 45 GHz. The broadband nature due to elimination of the air/dielectric interface is well demonstrated.

III. Fabrication

The fabrication of the coupler was performed based on the following steps (Fig. 5):

a) The coplanar waveguide (CPW) and the ground planes are patterned on top of the soda-lime glass substrate with ε_r of 7.75 by means of standard lift-off process using chromium and gold (Cr / Au; 30 nm / 1.5 µm).

b) Photo-definable epoxy SU-8 (Microchem, Inc.) is spin-cast and patterned for the post definition to the desired height, by which the substrate coupling is minimized. In this coupler implementation, feeding posts have the height of 190 µm

c) Conformal seed layers of titanium and copper (Ti / Cu; 30 nm / 300 nm) have been deposited using a DC sputterer. Negative-tone photo resist NR9-8000 (Futurrex, Inc.) is spin-coated and lithographically patterned, letting copper selectively cover the posts with a thickness of 15 µm

d) A thick sacrificial polymers (NR9-8000) has been used as a mechanical support for the subsequent bridge patterning

e) Seed layers of Ti / Cu for the bridge pattering are deposited, followed by photoresist (NR9-8000) casting and patterning on it. After copper electrodeposition with a thickness of 10 µm has been performed, removal of molding polymer, seed layers, and sacrificial layers follows to complete the process (e).

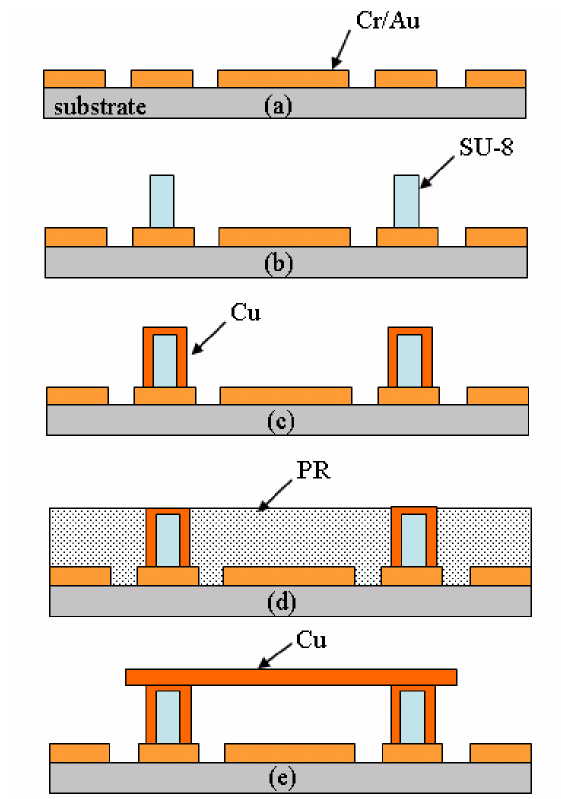
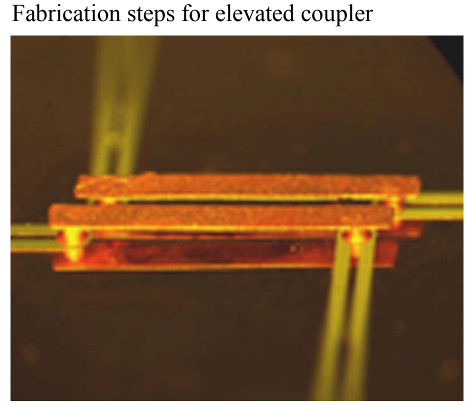
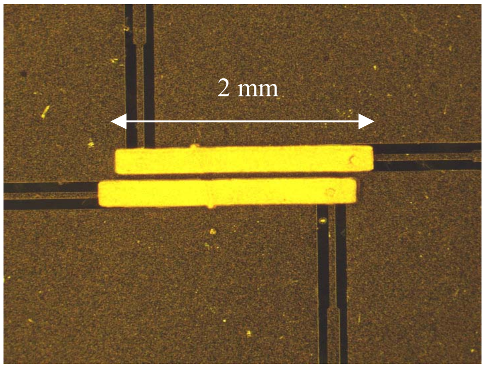


Fig. 5. Fabrication steps for elevated coupler



(a)



(b)

Fig. 6 (a) Top View (b) 3-D view of the fabricated prototype on glass

IV. Measurement Results

The fabricated prototype (Fig. 6) was characterized by a 2-port Agilent 8510C vector network analyzer with a probe station. The NIST Multical TRL algorithm [9] was used to calibrate the measurement system. Five lines were used. The reference plane was set to the step discontinuity where the quarter wavelength transformer is connected with the input coplanar waveguide. During characterization, two of the four ports were terminated with RF probes integrated with 50 Ω terminations.

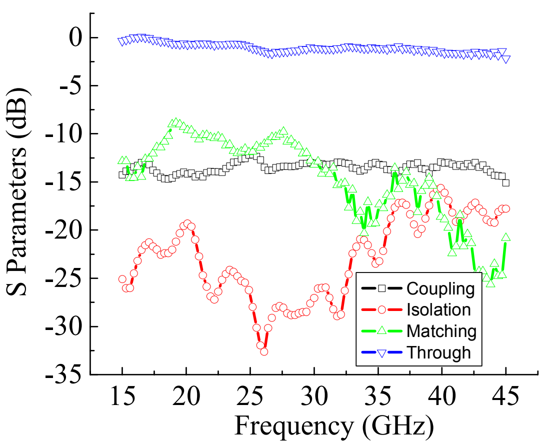


Fig. 7. Measured performance of elevated coupler

As shown in the measured results (Fig. 7.), the coupler demonstrates a very broadband coupling of 12.5 dB and a matching better than 10 dB over 15-45 GHz. It also shows a through transmission of 0.015-1.85 dB over 15-45 GHz, which agrees well with the simulation. Multi-section transformer can be used in future to get better return loss performance. It is believed that the disparities between the simulated and measured matching and coupling are caused by the imperfection of the 50 Ω termination impedance as well as the parasitics associated with the probes that are connected with those termination impedances. The calibration was not performed on those unused ports.

Multi-section coupler fabrication is in progress and it is believed to achieve more bandwidth.

V. Conclusion

In this paper, an ultra-broadband (15-45 GHz) 12.5 dB surface micromachined microstrip directional coupler is reported for the first time. Surface micromachining can significantly reduce the loss associated with the substrate, as well as the frequency dispersion due to the air/dielectric interface. Thick metal electroplating helps enhance the vertical wall coupling. The prototype is currently built on the soda-lime glass, but the fabrication processes can be easily applied to standard CMOS substrates, so this method can find application in the effort to integrate high performance RF components with digital or optical subsystem modules on low cost, low resistivity silicon substrates.

Acknowledgement

The authors wish to acknowledge the support of the Georgia Electronic Design Center (GEDC).

References

[1] R.R.Tummala, M.Swaminathan, M.M.Tentzeris, etc, ``The SOP for Miniaturized, Mixed-Signal Computing, Communication and Consumer Systems of the Next Decade", IEEE Transactions on Advanced Packaging, Vol.27 No.2, pp.250-267, May 2004.

[2] J.Papapolymerou, G.E.Ponchak and E.M.Tentzeris, "A Wilkinson Power Divider on a Low Resistivity Si Substrate with a Polyimide Interface Layer for Wireless Circuits", Proc. of the 2002 IEEE-IMS Symposium,, , pp.I.593-596, Seattle, WA, June 2002

[3] G.E. Ponchak, A. Margomenos and L. Katehi, “Low loss CPW on low resistivity Si substrates with a micromachined polyimide interface layer for RFIC interconnects,” IEEE Trans. Microwave Theory and Techniques, Vol. 49, No. 5, pp. 866-870, May 2001.

[4] D. M. Pozar, Microwave Engineering, 2nd ed. NewYork:Wiley, 1998, pp 392-394

[5] Kang, X.K., Ma, J., Li, L.W, etc, “Broadband directional couplers using multiple-section equivalent CPW lines” Proc. of Asia-Pacific Microwave Conference 2000, pp1319-1321, Sydney, Australia, Dec. 2000

[6] Krishnamurthy, L., Van Tuyen Vo; Sloan, R.; etc. “Broadband CPW multilayer directional couplers on GaAs for MMIC applications” High Frequency Postgraduate Student Colloquium, 2004, pp183-188, Manchester, UK, 6-7 Sept. 2004

[7] C.P. Wen, “Coplanar-Waveguide Directional Couplers.” Microwave Theory and Techniques, IEEE Transactions on , Volume: 18 , Issue: 6 , pp318-322, Jun 1970,

[8] Yong-Kyu Yoon, Jin-Woo Park, and Mark G. Allen, “RF MEMS Based on Epoxy-Core Conductors,” Digest of Solid-State Sensor, Actuator, and Microsystems Workshop 2002, , pp.374-375, Hilton Head Island, South Carolina, 2002

[9] R. B. Marks, “A multiline method of network analyzer calibration,” IEEE Trans. Microwave Theory Tech., vol. 39, pp. 1205–1215, Dec.1991