WE3E-5

A 10-50 GHz Micromachined Directional Coupler

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Abstract — **A 20 dB directional coupler has been designed and fabricated on a thin dielectric membrane using micromachining techniques. Design of the asymmetric tapered coupled line coupler relies on readily available models and ideal transmission line theory. The use of membrane technology results in less than 0.4 dB insertion loss in the coupler from 10 to 50 GHz. In addition, a micromachined packaging technique creates a shielded circuit which is extremely compact and lightweight.**

I. Introduction

Micromachined millimeter-wave transmission lines have shown very good performance, and have been used to create low-loss high-Q circuits such as filters [1],[2] and power dividers [3]. In addition, micromachined shielding cavities have been used to develop individually packaged circuits which provide additional benefits of compact size, light weight, and electromagnetic isolation [4]. This work pursues the development of a wide-band coupler with improved performance over existing planar coupler technologies, as well as reduced package size and weight.

The transmission line architecture in this work is known as shielded membrane microstrip (SMM). This structure has been used to realize high performance components for applications up to 110 GHz [1],[2]. It also provides the benefit of an integrated conformal package which enhances circuit performance while substantially reducing size and cost.

Directional couplers are of great importance for many types of microwave systems. In particular, measurement applications (e.g. network analysis) require precise knowledge of signal characteristics without great disruption of the signal being measured. This is typically accomplished through the use of a 10-20 dB directional coupler which provides low insertion loss to the measurement signal. This type of measurement requires high directivity, or isolation, within the coupler so that measurement errors are minimized.

The coupler presented in this paper is an asymmetric tapered coupled-line coupler. This type of coupler can be designed for any desired coupling level, and is derived from the Klopfenstein impedance taper [5]. It has a high pass response, and theoretically infinite bandwidth. In practice, of course, it is impossible to achieve infinite bandwidth due to the limitations of the transmission media used in the circuit realization. With micromachined structures such as SMM line, however, the high frequency limitations usually encountered by conventional planar structures are far less prohibitive. Therefore, the upper frequency limit of this circuit will be higher than that of a conventional planar coupler.

II. Design

Design of the coupler proceeds in a straightforward manner, since the outstanding propagation characteristics of SMM line allow the use of ideal transmission line theory throughout the design process. A schematic of the coupler circuit is illustrated in Fig. 1, and the procedure presented in [6] was followed. The length of the coupler was chosen to provide 20 dB coupling for frequencies above 20 GHz, thus $L = 4.5$ mm. The method given in [7] was used to calculate the impedance distribution for the taper, and the necessary SMM coupled-line dimensions were synthesized using the offset stripline model available in HP-EEsof LineCalc [8]. The SMM ground plane height, h, was 50 μm, and the cover height, h_c, was 500 μm.

III. Fabrication

Fabrication of SMM circuits is based on the use of a thin dielectric membrane which is suspended in air through bulk micromachining of the silicon carrier wafer. The membrane comprises three dielectric layers which are grown individually using standard silicon processing techniques. The $SiO_2/Si_3N_4/SiO_2$ composite structure is approximately 1.5 μm thick, and remains in slight tensile stress when the silicon substrate is selectively removed beneath it. It fully supports the circuit metallization patterns in an air dielectric environment.

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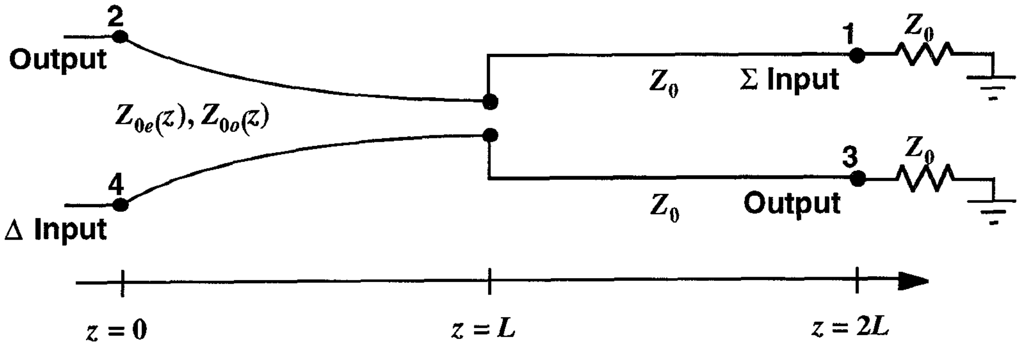

Figure 1. Circuit schematic of the asymmetric tapered coupled line coupler. The impedance distributions $Z_{0e}(z)$ and $Z_{0o}(z)$ are calculated from the Klopfenstein taper algorithm.

A two-dimensional representation of the SMM line geometry is shown in Fig. 2. The circuit and shielding wafers are fabricated separately and then assembled as shown. The depth of the cavity in the shielding wafer determines the ground plane separation of the SMM, while a metallized carrier wafer provides further electrical shielding. The cavity structures are formed by a selective wet etch in ethylenediamene pyrocatechol (EDP). In the case of the circuit wafer, the silicon is completely removed, and the dielectric membrane remains suspended over the micromachined cavity.

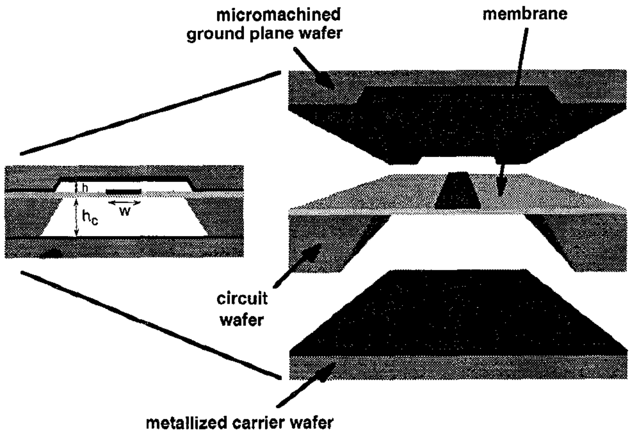

Figure 2. Cross section of the SMM line showing placement of the micromachined ground plane wafer on top of the membrane supported transmission line structure.

IV. Measurements

De-embedded on-wafer measurements of the micromachined coupler are accomplished using the MultiCal program from NIST [9] which employs the Thru-Reflect-Line method [10] of on-wafer calibration. The probes used are Picoprobe ground-signal-ground type probes with 150 µm pitch [11]. Transition to the shielded membrane microstrip geometry of the coupler is achieved through a Klopfenstein taper which serves two purposes: matching of the 50 Ω probe impedance to the 90 Ω coupler impedance; and conversion of the coplanar configuration of the wafer probes to the SMM geometry of the coupler [12]. In order to measure the full 4-port characteristics of the coupler using only a 2-port network analyzer, three identical couplers were fabricated, each designed for a different 2-port measurement. The unmeasured ports in each circuit were matched with microshield Klopfenstein tapers terminating in 70 Ω thin film resistors. The resistors were fabricated with evaporated Nichrome (Ni-Cr alloy, 40% Cr by weight) with a thickness of 700 Å. Individual resistors were measured to be 62 Ω at DC. A photograph of the taper/resistor termina-

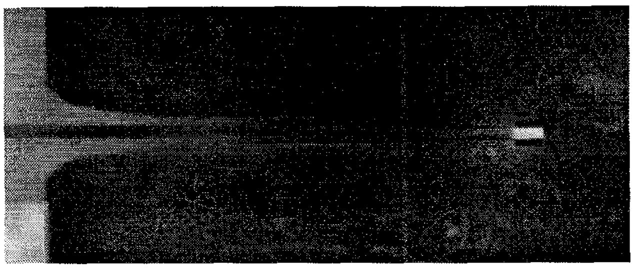

Figure 3. Photograph of the termination used for matching unmeasured ports during 2-port measurements of the micromachined coupler. The thin film resistor can be seen at the 70 Ω end of the 90 - 70 Ω matching taper.

tion used for the matched ports is shown in Fig. 3. Independent measurement of the termination shows that the return loss exceeds 14 dB up to 50 GHz, as shown in Fig. 4.

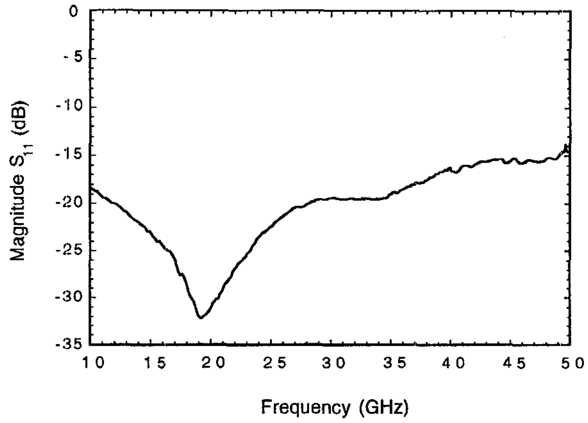

Figure 4. Measured input reflection coefficient of the resistive termination used to match the unconnected ports of the micromachined coupler. Maximum reflection is -15 dB at 50 GHz.

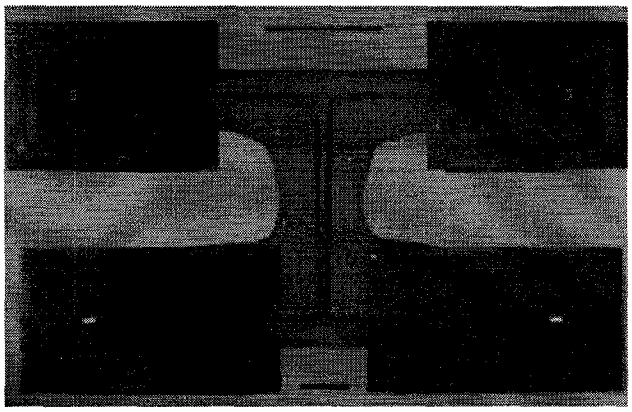

Figure 5. Photograph of the micromachined coupler. The membrane supported region appears darker than the surrounding silicon support rim, and it's maximum dimensions are 6 mm x 10 mm. This configuration was used to measure the coupled output of the coupler, with the direct and isolated ports matched by the resistive terminations.

The measured S-parameters of the micromachined coupler (see photograph, Fig. 5) are plotted in Fig. 6. The coupling (S_{31}) is 19.8 ± 1.7 dB from 10 to 50 GHz. The insertion loss (S_{21}), plotted separately in Fig. 7, is less than 0.4 dB up to 50 GHz. Improvements in the matching termination will result in higher isolation and tighter coupling response.

In terms of insertion loss, this coupler represents a significant performance improvement over conventional planar technology, and even rivals the performance of *Ka*-Band waveguide couplers (see Table 1). In addition, the integrated micropackage of this coupler is much smaller than standard microwave and waveguide circuit elements.

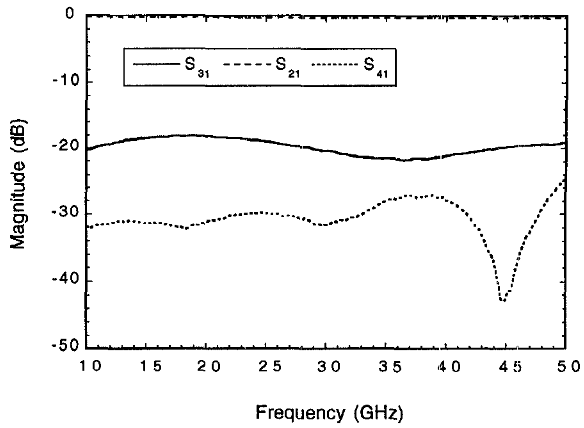

Figure 6. Measured performance of the micromachined coupler. Coupling is 19.8 ± 1.7 dB, with less than 0.4 dB insertion loss from 10-50 GHz.

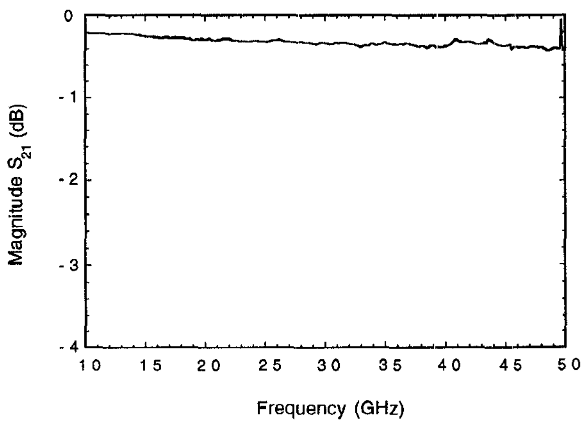

Figure 7. Expanded plot of the direct port output (S_{21}) of the micromachined coupler. Insertion loss is less than 0.4 dB over the measurement band.

Table 1: Comparison of the Micromachined Coupler to Commercially Available *Ka*-Band Couplers.

	This Work (10-50 GHz)	Planar Coupler[a] (18-40 GHz) [13]	Waveguide Coupler[b] (26.5-40 GHz) [14]
Coupling (dB)	19.8 ± 1.7	20 ± 1.25	20 ± 0.7
Insertion Loss (dB) max.	0.4	1.45	0.8
Package Volume (mm^3)	13 x 8 x 1.5	44.5 x 12.7 x 10.2	157.7 x 33.0 x 33.8

a. Includes coaxial connection
b. Referenced to waveguide flanges (WR-22).

V. Conclusions

A self-packaged micromachined directional coupler is presented. The coupler is completely shielded within a small, lightweight micropackage, and demonstrates 19.8 ± 1.7 dB coupling with less than 0.4 dB insertion loss from 10 to 50 GHz. The performance rivals that of commercially available couplers, at a fraction of the size and cost.

Acknowledgments

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References

[1] S. V. Robertson, L.P.B. Katehi, and G.M. Rebeiz, "Micromachined Self-Packaged W-Band Bandpass Filters," in *1995 IEEE MTT-S Digest*, pp. 1543-1546.

[2] C.-Y. Chi, G. M. Rebeiz, "Planar Microwave and Millimeter-Wave Lumped Elements and Coupled-Line Filters Using Micro-Machining Techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 4, pp. 730-738, Apr. 1995.

[3] T. M. Weller, L. P. B. Katehi, M. I. Herman, and P. D. Wamhof, "Membrane Technology (MIST-T) Applied to Microstrip: A 33 GHz Wilkinson Power Divider," in *1994 IEEE MTT-S Digest*, pp. 911-914.

[4] R. F. Drayton and L. P. B. Katehi, "Development of Self-Packaged High Frequency Circuits Using Micromachining Techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 9, pp. 2073-2080, Sep. 1995.

[5] R. W. Klopfenstein, "A Transmission Line Taper of Improved Design," *Proc. IRE*, vol. 44, pp. 31-35, Jan. 1956.

[6] D. M. Pozar, *Microwave Engineering*. New York: Addison-Wesley, 1990.

[7] M. A. Grossberg, "Extremely Rapid Computation of the Klopfenstein Impedance Taper," *Proc. IEEE*, vol. 56, pp. 1629-1630, Sep. 1968.

[8] Hewlett-Packard Company, Santa Clara, CA.

[9] R. B. Marks and D. F. Williams, Program MultiCal, rev. 1.00, NIST, August, 1995.

[10] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," *IEEE Trans. Microwave Theory Tech.*, Vol. 39, pp. 1205-1215, July 1991.

[11] GGB Industries, Inc., Naples, FL.

[12] S. V. Robertson, L. P. B. Katehi, and G. M. Rebeiz, "Micromachined W-Band Filters," to be published in *IEEE Trans. Microwave Theory Tech.*

[13] Loral Microwave - Narda, Hauppauge, NY.

[14] Millitech Corporation, South Deerfield, MA.