Micromachined Self-Packaged W-Band Bandpass Filters

Stephen V. Robertson, Linda P. B. Katehi, and Gabriel M. Rebeiz

The University of Michigan
Radiation Laboratory
Ann Arbor, MI 48109

Abstract— **Experimental and theoretical results are presented for membrane supported W-band bandpass filters which utilize silicon micromachining technology to create self-packaged, shielded circuits. A coupled line shielded microstrip implementation of a 5-element 0.5 dB equal ripple Chebyshev filter achieves a minimum insertion loss of 3.4 dB with a 6.1% bandwidth centered at 94.7 GHz. The measured filter performance shows very sharp cutoff with out of band attenuation better than 25 dB and input return loss better than 8 dB. Results are also presented for a 5-element filter that achieves a minimum insertion loss of 2.2 dB with an 11.3% bandwidth centered at 94.7 GHz, and a 3-element filter with 1.3 dB insertion loss and 16.4% bandwidth at 94.9 GHz. Efforts to model filter performance using commercially available software and FDTD techniques are discussed.**

I. Introduction

Planar microwave and millimeter-wave circuits take advantage of microelectronics processing technology to realize compact, low-cost, high-performance applications. As the operating frequency increases, however, planar circuits fabricated on typical silicon and gallium arsenide substrates begin to suffer from power loss through substrate modes and dispersion caused by the discontinuity in permittivity at the dielectric/air interface. At even higher frequencies, these problems become prohibitive and realization of microwave circuits such as filters and couplers becomes very difficult.

Recently, efforts have been made to reduce or eliminate these problems by utilizing silicon micromachining techniques. One method employs selective silicon etching to remove the substrate underneath planar circuits which are then supported by thin dielectric membranes in free space [1]. This technique has resulted in a new type of transmission line called microshield line which has very low loss and nearly zero dispersion up to frequencies as high as a few terahertz [2]. Circuit components realized in microshield line have shown excellent performance compared to conventional ones [3],[4], and microshield line has shown excellent performance in planar W-Band low-pass filters [5]. In addition, silicon micromachining allows for the development of miniature self-packaged components appropriate for densely packaged microwave and millimeter-wave circuit applications [6].

In this work, we present a series of self-packaged bandpass filters which have been realized in W-Band using micromachining techniques. The filters are implemented in shielded microstrip coupled line geometries and employ dielectric membranes and micromachined shielding cavities. Measured results presented here show very high performance, low loss bandpass filters that are centered at approximately 94 GHz and have bandwidths ranging from 6% to 16.4%. The filters were designed using commercially available software and low frequency scale modeling. Finite difference time domain analysis [7] was used to verify the design and confirm the measurements.

II. Filter Design

The filters were designed for coupled line shielded microstrip implementations using the commercially available software package PARFIL [8] running on an IBM compatible PC. Filter parameters were calculated for a ground plane spacing of 100 μm and an upper shielding height of 500 μm. The designs used an internal impedance of 90 Ω and assumed an air dielectric everywhere. Three 94 GHz filters were designed using PARFIL, with two 5-element filters designed for bandwidths of 4.3% and 8.5%, and a 3-element filter designed for 12.8% bandwidth.

TH 3F

The filter designs were optimized by constructing a 47:1 scale model of the 4.3% bandwidth 5-element filter designed for 2.00 GHz. A 76 μm thick polyethylene film was suspended over an aluminum sheet metal ground plane, with circuit metallization patterns defined on the polyethylene using copper tape. Measurements of the model filter on an HP 8720B 2-port network analyzer revealed a filter center frequency of 1.958 GHz, and measured bandwidth of approximately 3.5%, which agreed fairly well with the calculated performance. Through further experimental iteration, it was found that the resonator lengths required shortening by 5.3% to shift the center fre-

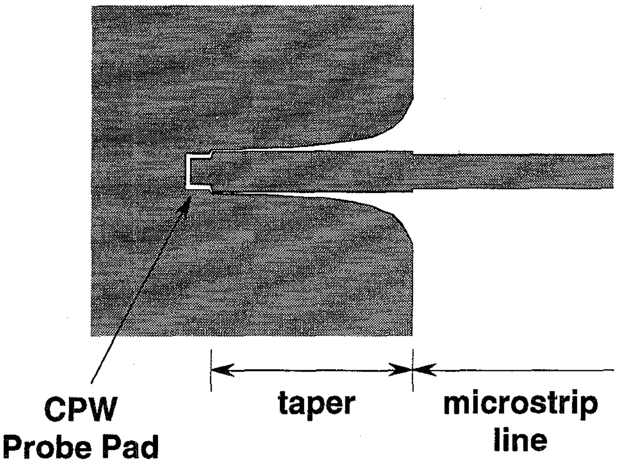

Fig. 1. The Klopfenstein taper as a CPW-to-microstrip transition.

quency up to the desired value. FDTD analysis at 94 GHz verified the findings of the low frequency modeling experiment.

To facilitate on-wafer probing measurements, a matching network was designed to transition from a CPW-style probe pad to microstrip. Since the filter design impedance was 90 Ω and the probing system was matched to 50 Ω, the CPW-to-microstrip transition had a dual purpose: (1) to transform the circuit impedance from 50 Ω to 90 Ω, and (2) to transfer the fields from a horizontally opposed CPW type distribution to a vertically oriented microstrip distribution. To accomplish these two tasks, a Klopfenstein taper and a microshield line geometry were chosen. The Klopfenstein taper was geometrically desirable since it promoted a gradual transfer from the CPW mode to the microstrip mode, and microshield line has been shown to support both of these modes [9].

The taper was designed using a point matching method (PMM) algorithm [10] to calculate the characteristic impedance of the microshield line for various 2-dimensional geometries. For a 220 μm constant width center conductor, it was found that varying the slot width from 10 μm to 290 μm produced the desired range of impedances from 55 Ω to 81 Ω. These results were used to design the taper shown in figure 1 based on the method found in [11]. At the beginning of the transition, the narrow slots of the microshield line promote a high horizontal field concentration which is compatible with the wafer probe geometry. At the end of the transition, where the impedances approach the higher range, the slots of the microshield line are much wider (as wide as twice the height above the ground plane), forcing the fields to concentrate in the area between the center conductor and the lower ground plane, like a microstrip mode. At the end of the taper, the CPW upper ground planes are terminated, and the pure microstrip mode is launched.

III. Measurements

The filters were fabricated on 500 μm thick high resistivity wafers with dielectric membranes grown on both sides using anisotropic silicon etching [5] (see figure 2). Three stacked wafers form the self-packaged shielded microstrip assembly, which is illustrated with a 2-dimensional cross-section in figure 3 . Micromachining of the ground plane wafer was implemented using a two step etch process [6] which allowed the creation of windows for on-wafer probing measurements (figure 4).

The measurements were performed using an HP 8510C Vector Network Analyzer with Model 120 Picoprobe

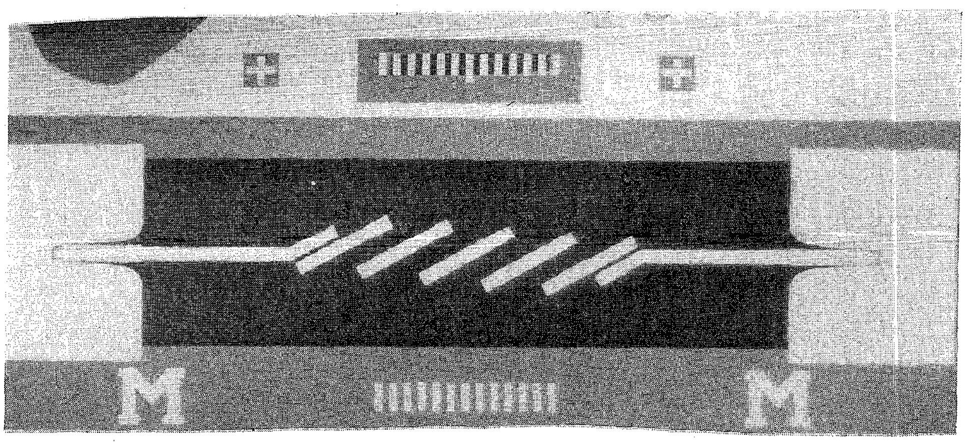

Fig. 2. Photograph of the 4.3% designed bandwidth coupled line filter after selective removal of the silicon substrate. The membrane area appears darker than the surrounding silicon support rim.

The discrepancy in bandwidth occurs since the FDTD analysis does not consider the effect of the thin dielectric membrane. The presence of the membrane slightly increases the capacitances of the even and odd mode impedances in the coupled line sections, thereby increasing the bandwidth and the center frequency of the filter. Previous measurements of microshield line components have shown that the membrane does influence the response of membrane supported circuits [3].PARFIL is used to include conductor loss in the filter analysis, since the FDTD code does not treat the finite conductivity of the metal. A value of 2.44×10^{-8} Ω-cm for the resistivity of gold is used, and the surface roughness is assumed negligible since the gold was evaporated. The loss tangent is taken to be zero in the air

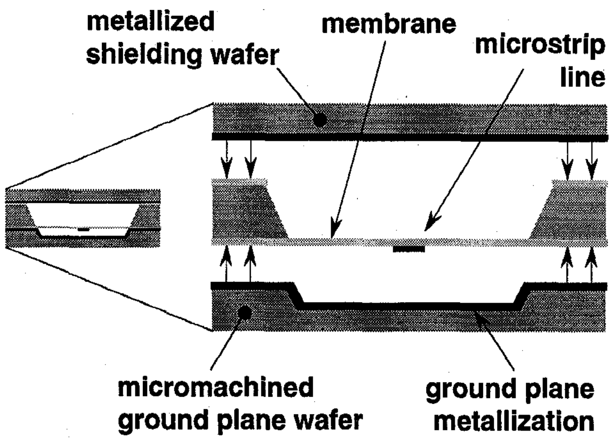

Fig. 3. Two-dimensional geometry of the micromachined shielded microstrip.

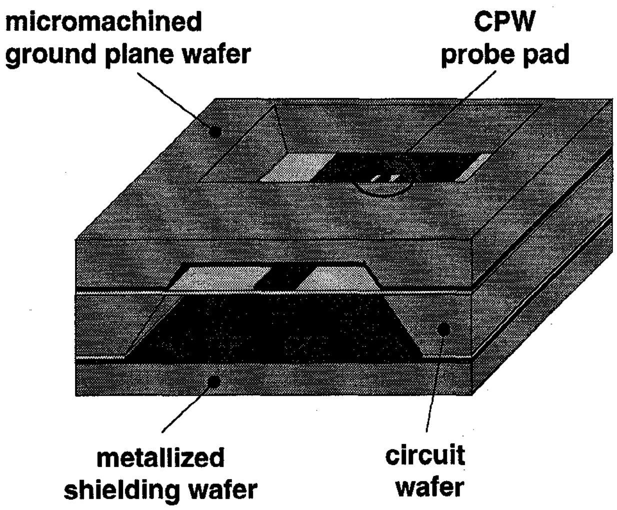

Fig. 4. A 3-dimensional view of the self-packaged membrane microstrip geometry, showing the micromachined probe window and exposed CPW probe pad.

150 μm pitch coaxial probes. A through-reflect-line (TRL) calibration was performed using the NIST de-embedding software and the following circuits: a 4 mm thru line, a 6 mm delay line, and a 2 mm offset open.

The measured response of the 5-element, 4.3% bandwidth filter is shown in figure 5. The filter achieves an average passband insertion loss of 3.4 dB and a wider than designed bandwidth of 6.1% at a center frequency of 94.7 GHz. The plot in figure 6 compares the measured insertion loss with that predicted by the FDTD analysis.

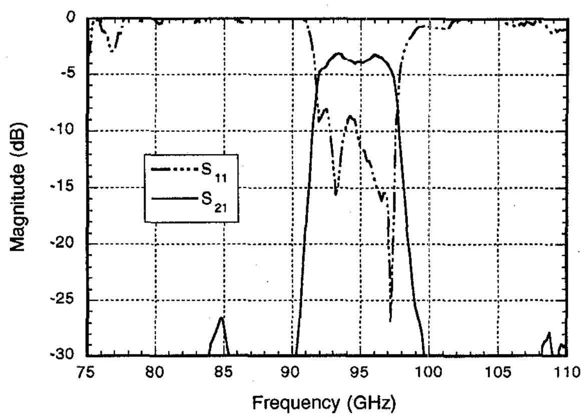

Fig. 5. Measured S-parameters of a 5-element bandpass filter with 3.4 dB insertion loss, 6.1% bandwidth, and 94.7 GHz center frequency.

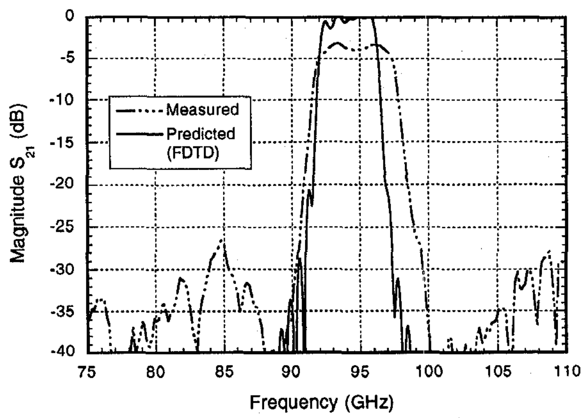

Fig. 6. FDTD results compared with the measured insertion loss of a 5-element bandpass filter.

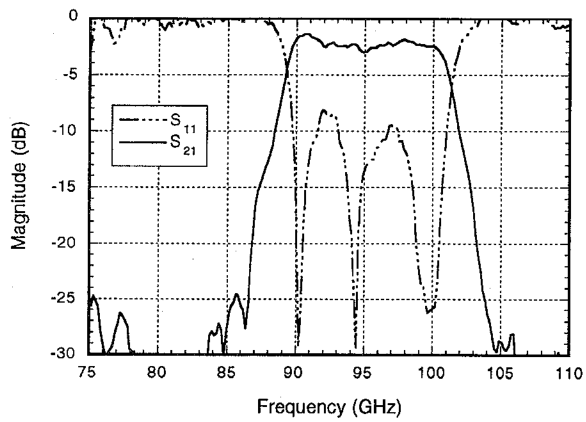

Fig. 7. Measured S-parameters of a 5-element bandpass filter with 2.2 dB insertion loss, 11.3% bandwidth, and 94.7 GHz center frequency.

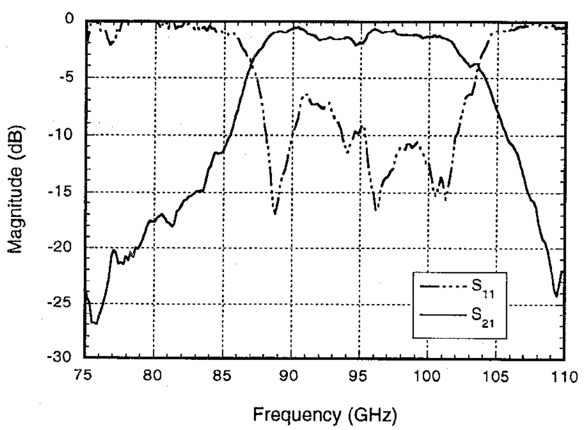

Fig. 8. Measured S-parameters of a 3-element bandpass filter with 0.6 dB minimum insertion loss, 16.4% bandwidth, and 94.9 GHz center frequency.

dielectric. The loss in the filter is observed to be due entirely to conductor loss, since the measured insertion loss of 3.4 dB agrees very well with the calculated value of 3.3 dB.

The measured S-parameters of two other filters are depicted in figures 7 and 8. The response plotted in figure 7 of a 5-element filter designed for 8.5% bandwidth indicates a passband insertion loss of approximately 2.2 dB with an 11.3% bandwidth centered at 94.7 GHz. Measurements of a 3-element, 12.8% designed bandwidth filter are shown in figure 8. This filter has a passband insertion loss of 1.3 dB, a center frequency of 94.9 GHz, and a bandwidth of 16.4%.

IV. Conclusions

We have presented high performance planar W-Band bandpass filters which are fabricated using silicon micromachining and membrane technologies. Micromachining of multiple wafers provides a shielded assembly which can be integrated as a self-packaged unit. The filters display excellent performance as measured on a W-Band probe station, including low passband insertion loss and high out of band signal rejection. The theoretical results match the measurements very well.

V. Acknowledgments

This work was supported by NASA. The authors wish to thank Dr. N. Dib for providing the FDTD code and Mr. G. Ponchak at NASA Lewis Research Center for his time and for the use of the W-Band network analyzer and the wafer probing apparatus.

References

[1] N.I. Dib, W. Harokopus, L.P.B. Katehi, C.C. Ling, and G.M. Rebeiz, "Study of a Novel Planar Transmission Line," *1991 IEEE MTT-S Digest*, pp. 623-6.

[2] H. Cheng, J.F. Whitaker, "Terahertz-Bandwidth Characterization of Coplanar Waveguide on Dielectric Membrane via Time-Domain Electro-Optic Sampling," *1994 IEEE MTT-S Digest*, Vol. 1, pp. 477-80.

[3] T.M. Weller, L.P.B. Katehi, and G.M. Rebeiz, "High Performance Microshield Transmission Line Components," *to be published in the IEEE Trans. MTT*, March 1995.

[4] C.Y. Chi, G.M. Rebeiz, "A Low-loss 20 GHz Bandpass Filter," *to be published in the 1995 IEEE MTT-S Digest*, May 1995.

[5] S.V. Robertson, L.P.B. Katehi, and G.M. Rebeiz, "W-Band Microshield Low-Pass Filters," *1994 IEEE MTT-S Digest*, Vol. 2, pp. 625-8.

[6] R.F. Drayton, L.P.B. Katehi, "Development of Miniature Microwave Circuit Components Using Micromachining Techniques," *1994 IEEE MTT-S Digest*, Vol. 1, pp. 225-8.

[7] N.I. Dib, L.P. Katehi, "Analysis of the Transition from Rectangular Waveguide to Shielded Dielectric Image Guide Using the Finite-Difference Time-Domain Method," *IEEE Microwave and Guided Wave Letters*, Vol. 3, pp. 327-329, September 1993.

[8] WaveCon EM Wave Control Software, P.O. Box 2697, Escondido, CA 92033.

[9] T.M. Weller, G.M. Rebeiz, L.P. Katehi, "Experimental Results on Microshield Transmission Line Circuits," *1993 IEEE MTT-S Digest*, Vol. 2, pp. 827-830.

[10] N.I. Dib, L.P.B. Katehi, "Theoretical Characterization of Coplanar Waveguide Transmission Lines and Discontinuities," PhD Thesis, University of Michigan, November 1992.

[11] D.M. Pozar, *Microwave Engineering*, Reading, MA: Addison-Wesley Publishing Company, 1990, pp. 321-4.