Millimeter and Submillimeter Wave Microshield Line Components

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

NASA Center for Space Terahertz Technology
The University of Michigan
Ann Arbor, MI 48109

Abstract

Recent efforts at the University of Michigan have resulted in the successful development of high-performance planar components which operate in Ka- and W-Bands. These circuits are fabricated using silicon micromachining techniques, and they are placed on a thin dielectric membrane which is shielded by a metallized cavity on one side (see Fig. 1). This type of line, called microshield line, has exhibited very low radiation and ohmic losses for frequencies as high as 1 THz.

A variety of microshield components have been fabricated and their performance has been measured at the facilities of the Radiation Laboratory at the University of Michigan and NASA Lewis Research Center. These circuit components exhibit superior performance compared to planar components made with conventional microstrip or coplanar technology. In this paper, basic transmission line properties such as dispersion and attenuation are first examined. This is followed by a sample of the measured results obtained at Ka-Band for right angle bends, low-pass filters, and band-pass filters. Furthermore, extension of this technology to higher frequencies is explored.

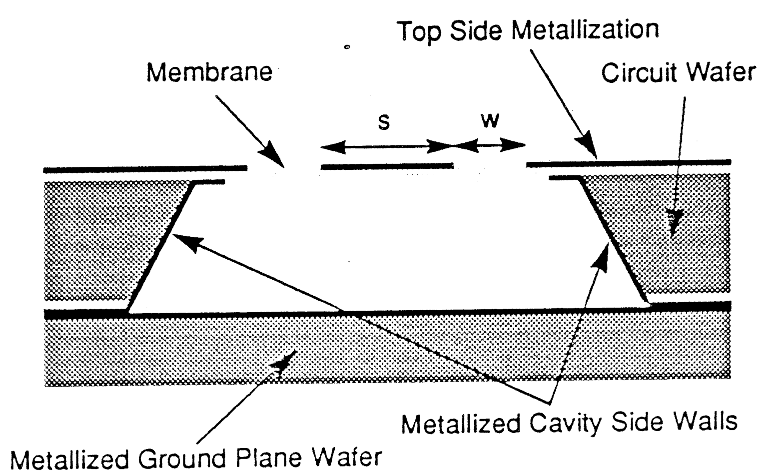

Figure 1. Microshield line uses micromachining techniques to suspend components in air on a thin dielectric membrane.

1. Introduction

The need for high performance microwave circuit components which could operate in the THz freqeuncy range led to the development of the microshield line in 1991 [1]. Microshield line uses silicon micromachining and membrane technology to locally remove the substrate underneath a conventional CPW type transmission line. The resulting configuration propagates a pure TEM wave in a homogeneous air dielectric with very low loss and virtually no dispersion over an extremely wide bandwidth [2].

In this work we present results showing the high performance characteristics of microshield line. Measurements of loss and effective dielectric constant show the low loss and low dispersion as expected. Microshield line components are compared to conventional planar components. In particular, right angle bends show better return loss performance when fabricated with microshield line instead of CPW. Also, planar filters for high frequency applications which normally suffer due to the presence of a dielectric substrate are shown to operate effectively when implemented using microshield line.

2. Fabrication

Microshield circuits are fabricated on high-resistivity (> 2,000 Ω-cm) silicon wafers with a 1.5 μm-thick $SiO_2/Si_3N_4/SiO_2$ composite deposited on both sides [3]. After the circuit metallization is patterned on the top side of the wafer using evaporation and lift-off, infrared alignment is used to pattern the backside membrane. The membrane layers are then etched to expose the silicon, at which point ethylenediamene pyro-catechol (EDP) anisotropic silicon etchant is used to define cavities underneath the circuit metallization. Once the silicon has been etched away, the top side membrane remains in tension to support the circuits. Next, the cavity side walls are metallized using a shadow mask evaporation which prevents an RF short from occurring between the signal line and the upper ground planes. Finally, the wafers are placed on a metallized ground plane wafer to completely shield the cavity (2-D geometry shown in Fig. 1).

3. Microshield Line Characteristics

A. *Effective Dielectric Constant*

Due to the air substrate of the microshield line, the effective dielectric constant, $\varepsilon_{r,eff}$, is very close to 1. The presence of the membrane, however, causes a slight increase in $\varepsilon_{r,eff}$ since a fraction of the fields will be contained within the thin dielectric layers which have relative dielectric constants of 3.9 (SiO_2) and 7.5 (Si_3N_4). As shown in Figure 2, the measured $\varepsilon_{r,eff}$ changes from around 1.09 to 1.15 as the slot width is reduced from 55 to 25 μm. This increase is a result of greater field confinement in the slot and thus in the membrane, and represents a decrease of nearly 3% in the guided wavelength. This dependence on the slot width is similar to the characteristics of CPW lines on a substrate such as GaAs or quartz [4]. As the line geometry approaches single micrometer dimensions which are comparable to the membrane thickness, $\varepsilon_{r,eff}$ could increase to around 2.0.

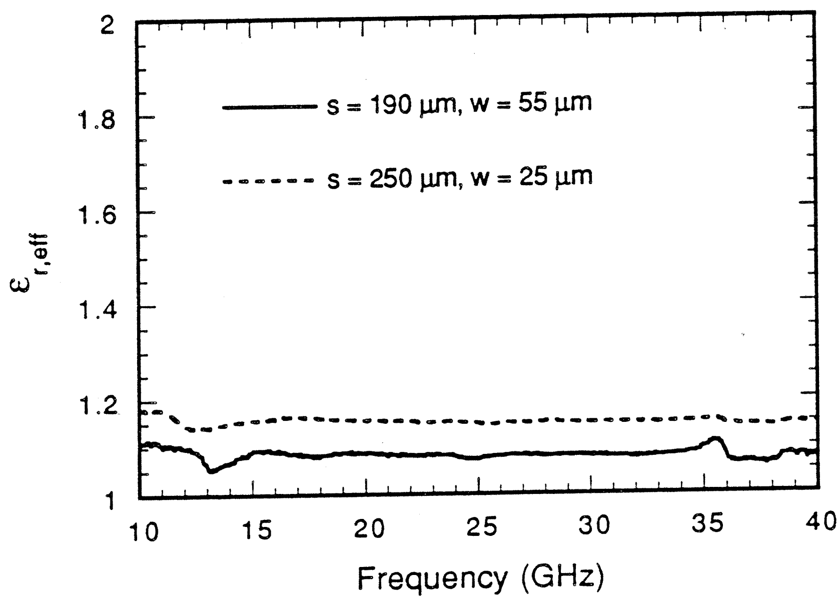

Figure 2. Effective dielectric constant at Ka-Band for two geometries of microshield line.

B. Attenuation

The attenuation characteristics of the microshield line have been investigated by comparing measured data on different microshield geometries against experimental and theoretical results for coplanar waveguide which are found in the literature. At low frequencies, the two types of lines are expected to perform equally well, since dielectric and radiative losses are relatively small and attenuation is dominated by conductor loss, which should be about the same in microshield and CPW due to the similar geometry of the metallization. At higher frequencies, however, the microshield line gains an increasing advantage since it has essentially zero dielectric loss and does not radiate energy into the substrate, as with a substrate-supported CPW line. This characteristic has been verified by recent electro-optic sampling experiments, which have provided attenuation data on membrane lines up to 1000 GHz [2].

The comparison between the microshield and CPW attenuation is shown in Figure 3. The curves shown for comparison were chosen either because the CPW dimensions are similar to the microshield dimensions (curves C,F,G) or to illustrate the effects of reducing the line geometry (curves D,E). All pertinent geometrical parameters for the CPW and microshield examples are given in Table 1 beneath the figure, and it is noted that the conductor thickness is only about 2 skin depths at 25 GHz for all but two cases (note: the technique used in [5] assumes zero conductor thickness).

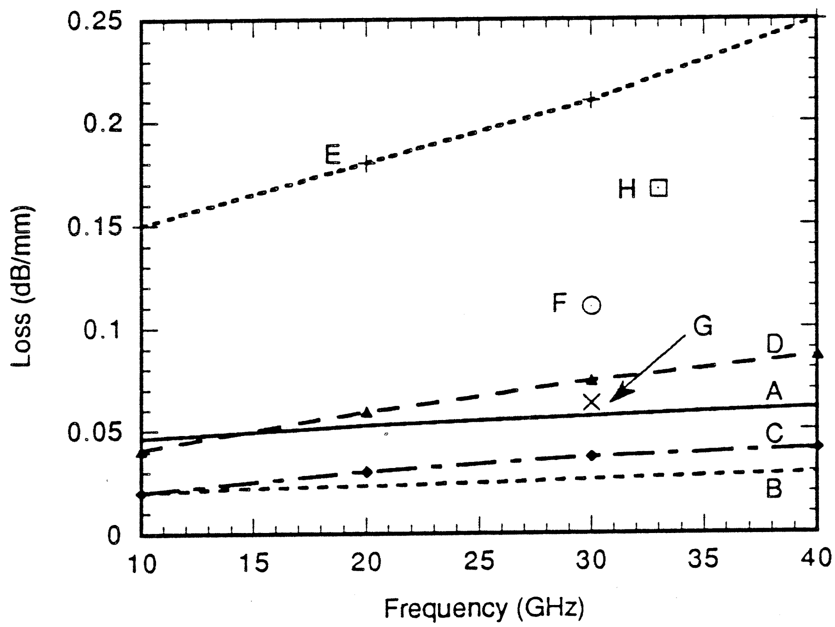

Figure 3. Comparison of microshield and CPW attenuation.

Table 1. Attenuation for microshield and coplanar waveguide lines. S is the center conductor width, W the slot width, H the substrate height, and t the metal thickness (in μm). The width of the lower shielding cavity for the microshield lines is 1800 μm.

Curve	Line	ε_r	Substr.	S	W	H	t	Z_0 (Ω)	Data	Ref
A	μshield	1.0	Air	250	25	355	1.2	75	Meas	—
B	μshield	1.0	Air	190	55	355	1.2	100	Meas	—
C	CPW	12.8	GaAs	232	84	100	—	50	Calc	[5]
D	CPW	12.8	GaAs	69	28	100	—	50	Calc	[5]
E	CPW	12.9	GaAs	88	16	500	1.0	30	Meas	[6]
F	CPW	12.9	GaAs	250	25	500	1.0	30	Calc	[4]
G	CPW	4.0	Quartz	250	25	250	1.0	50	Calc	[4]
H	GCPW	11.7	Si	50	125	355	1.2	73	Meas	—

The results presented here confirm that the microshield line is free from unexpected or excessive conductor-loss mechanisms, and has performance which is comparable to conventional substrate-supported coplanar waveguide at lower frequencies. Furthermore, the absence of dielectric-related loss and the ability to maintain non-dispersive, single-mode propagation over a very broad bandwidth lead to low attenuation well into the millimeter-wave frequencies.

4. Microshield Line Components

A. *Right Angle Bends*

A very common circuit 'element' in millimeter-wave systems is the right-angle bend. This structure gains significance with increasing frequency due to the parasitic capacitance and inductance which are associated with the abrupt change in the field orientation. These problems, combined with mode-conversion, result in a high reflection of the incident power (large S_{11}). In coplanar waveguide designs, the typical means of improving the return loss is to utilize air-bridges or dielectric overlays [7]. Both of these techniques are meant to offset the effects of different electrical path lengths along the two slots. Without this type of compensation, the asymmetry of the CPW right-angle bend will lead to excitation of the unwanted slot-line mode.

Many of the problems inherent to bends which are printed on conventional CPW can be minimized with the microshield geometry. The absence of the high dielectric constant material has two important effects: it leads to a reduction in the parasitic capacitance and, for a fixed physical size, it reduces the difference in electrical path lengths through the two slots. The shielding cavity, furthermore, provides continuous ground plane equalization without introducing additional discontinuities, thus improving upon conventional air-bridges. A comparison between the measured performance of a microshield-line bend and a typical CPW bend on GaAs [8] is shown in Figure 4; the microshield bend has an S_{11} which is at least 8 dB lower over the 10-40 GHz band. The noise in the data below 18 GHz is due to calibration error.

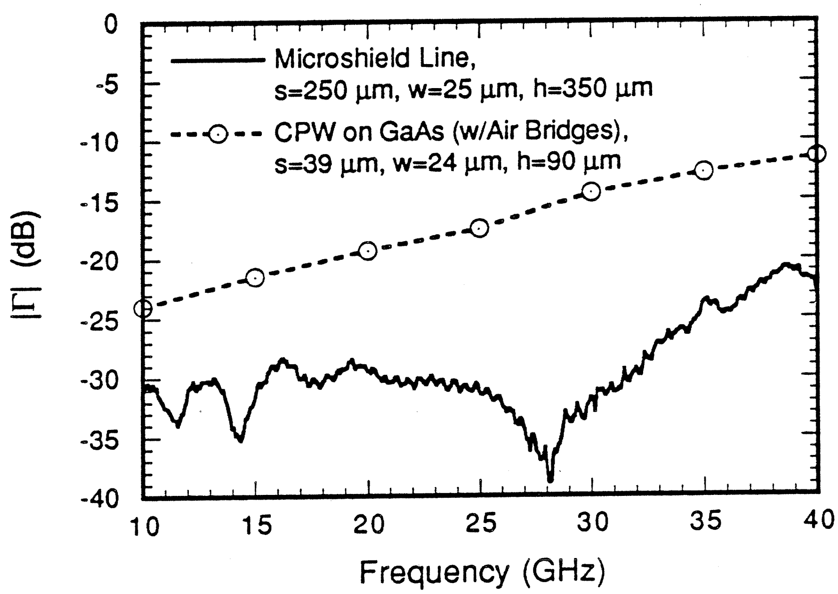

Figure 4. Performance of microshield and CPW right-angle bends.

B. Low-Pass Filters

The stepped-impedance approach to low-pass filter design is a relatively easy technique to use, and it is well suited for applications which do not require a sharp roll-off in the insertion loss. Often, however, the filter specifications call for high rejection over multiple-octave bandwidths, a requirement which may be difficult to meet using conventional substrate-supported lines due to the propagation of higher order modes. Thus, the very broad, single-mode bandwidth of the microshield line can provide superior filter performance in this respect. In addition, the absence of dielectric-related loss reduces both attenuation and parasitic radiation, resulting in very low passband insertion loss.

Stepped-impedance filters using 5-, 7-, and 9-sections have been designed and tested. Some of the results were previously presented in [9], where it was shown that the measured performance compared very well with ideal transmission line theory, as a result of the pure TEM nature of the microshield propagating mode. In Figure 5, measured data for a 5-section filter is compared with results from a full-wave moment-method analysis. The rejection is greater than 20 dB up to 75 GHz, which is about 1.5 octaves above the 3-dB point at 26 GHz. The measured passband insertion loss of this filter is between 0.2 and 0.5 dB from 20-23 GHz.

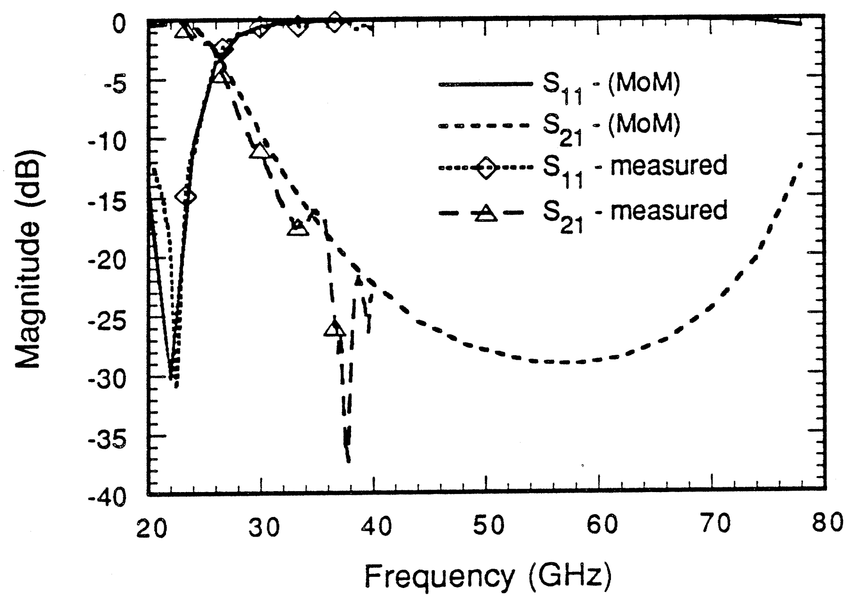

Figure 5. Performance of a 5-section stepped-impedance low-pass filter.

C. Band-Pass Filters

By cascading multiple open-end tuning stubs in series, it is quite simple to realize a bandpass response with high out-of-band rejection and low insertion loss. The geometry of a three-stage design is shown in Figure 6, in which each section is separated by 150 µm. The measured response, shown in Figure 7, has an insertion loss of only 1.0 dB from 22-32 GHz, which is competitive with the best shielded bandpass filters using suspended stripline [10]. The performance of this microshield filter could be further improved using thicker metallization (since the one micron thickness is equivalent to just over two skin-depths) or larger slot widths to minimize the conductor loss. The calculated data included in the plot is generated by using the scattering parameters found from the full-wave analysis of a single stub section and treating the filter as three non-coupled elements in series. The agreement between the measured and calculated performance is quite good and indicates that there is very little electromagnetic coupling between the stubs, even though the stub separation is only 150 µm. The response of the filter can also be modeled almost exactly by cascading the *measured* results for a single stub, and this approach accurately predicts the 1.0 dB insertion loss.

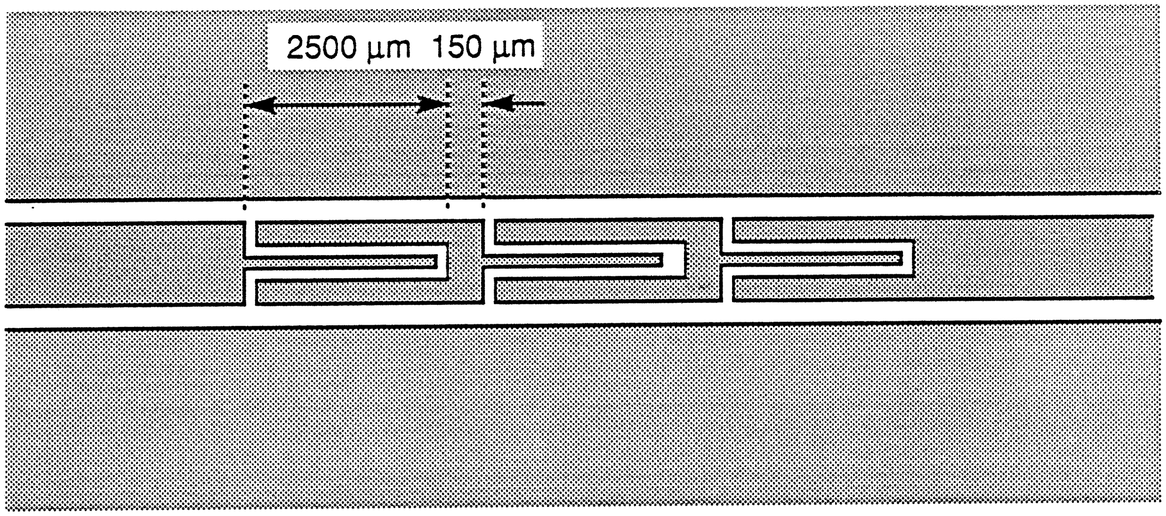

Figure 6. Geometry of a microshield line bandpass filter.

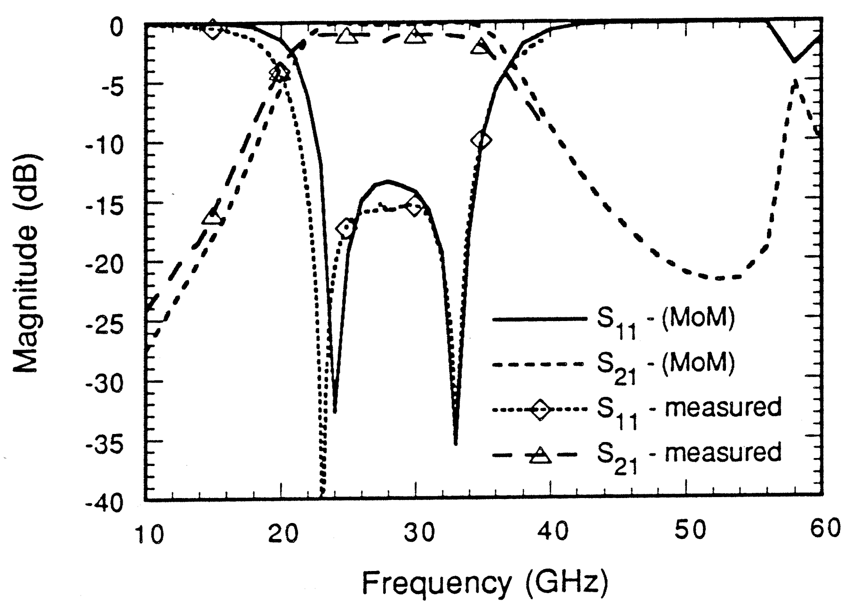

Figure 7. Performance of a microshield line bandpass filter.

5. Conclusions

Microshield line has been shown to be a very low loss, low dispersion transmission line well into the sub-millimeter wave frequency range. This work has demonstrated microshield circuit components with excellent performance at frequencies as high as 40 GHz, and continuing work at the University of Michigan has realized a 90 GHz low-pass filter and a 250 GHz band-pass filter. This recent work will be presented in detail in forthcoming publications.

6. Acknowledgments

This work was supported by the NASA Center for Space Terahertz Technology and the Office of Naval Research.

References

[1] N.I. Dib, W.P. Harokopus Jr., L.P.B. Katehi, C.C. Ling, and G.M. Rebeiz, "Study of a Novel Planar Transmission Line," *1991 IEEE MTT-S Digest*, pp. 623-626.

[2] H. J. Cheng, J. F. Whitaker, T. M. Weller, and L. P. Katehi, "Terahertz-Bandwidth Characterization of Coplanar Waveguide on Dielectric Membrane via Time-Domain Electro-Optic Sampling," *Presented at the 1994 MTT-S International Microwave Symposium.*

[3] G.M. Rebeiz, D.P. Kasilingam, Y. Guo, P.A. Stimson, D.P. Rutledge, "Monolithic Millimeter-Wave Two-Dimensional Horn Imaging Arrays," *IEEE Trans. Antennas and Propagation*, Vol. 38, pp. 1473-1482, September 1990.

[4] W. H. Haydl, W. Heinrich, R. Bosch, M. Schlechtweg, P. Tasker, and J. Braunstein, "Design data for millimeter wave coplanar circuits," *1993 European Microwave Conference Proceedings*, pp. 223-228.

[5] M. Zhang, C. Wu, K. Wu, and J. Litva, "Losses in GaAs Microstrip and Coplanar Waveguide," *1992 IEEE MTT-S Digest*, pp. 971-974.

[6] W. H. Haydl, J. Braunstein, T. Kitazawa, M. Schlechtweg, P. Tasker, and L. F. Eastman, "Attenuation of Millimeterwave Coplanar Lines on Gallium Arsenide and Indium Phosphide Over the Range 1-60 GHz," *1992 IEEE MTT-S Digest*, pp. 349-352.

[7] R. N. Simons and G. E. Ponchak, "Modeling of Some Coplanar Waveguide Discontinuities," *IEEE Trans. Microwave Theory Tech.*, Vol. 36, December, 1988, pp. 1796-1803.

[8] Amjad A. Q. Omar, "An Accurate Solution of 3-D Coplanar Waveguide Circuits," Ph.D. Thesis, University of Waterloo, Waterloo, Ontario, Canada, 1993.

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

[10] W. Menzel, "Broadband Filter Circuits Using an Extended Suspended Substrate Transmission Line Configuration," *Proceedings of the 22nd European Microwave Conference*, Aug. 24-27, 1992, pp. 459-463.