W-BAND MICROMACHINED FINITE GROUND COPLANAR (FGC) LINE CIRCUIT ELEMENTS

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1.0 *ABSTRACT*

This paper describes the development and characterization of Si-micromachined Finite Ground Coplanar (FGC) circuit components between 2 and 110 GHz. FGC lines are micromachined to eliminate the dielectric in the aperture regions, where the electromagnetic fields concentrate, in an effort to further improve their propagation characteristics and to provide loss levels only demonstrated by membrane lines. Measured results have shown a loss improvement of 1 dB/cm at 94 GHz. A micromachined FGC bandpass filter has shown a .8 dB improvement in insertion loss at 94 GHz over a conventional FGC line. Therefore, this approach offers an excellent alternative to the membrane technology, exhibiting very low loss, no dispersion, and mode free operation without using membranes to support the metallic structures.

2.0 *INTRODUCTION*

As shown recently [1, 2], Finite Ground Coplanar (FGC) lines provide an excellent alternative to conventional microstrip or coplanar waveguide for millimeter- and sub-millimeter-wave applications. Their low loss characteristics, in addition to their capability to operate on a variety of substrates with neither backside metallization nor vias for ground equalization, have made them exceptional candidates for high-frequency, low-cost, high-performance circuits. Their mode free operation allows excellent agreement between measured data and LIBRA's quasi-static modeling up to 110 GHz [1, 3]. The exhibited low loss at W-band has resulted in stubs and filters with performance characteristics comparable with the best recently reported membrane filters. Additionally, the use of FGC lines in W-band detectors has demonstrated bandwidths in excess of 30% and sensitivities as high as 3100 V/W. Furthermore, multiplier circuits based on this type of line have demonstrated very high power levels at frequencies exceeding 77 GHz.

The study of FGC lines has demonstrated that line loss is predominantly due to ohmic loss in the metallic conductors. This is not to say that the excited field is unaffected by the dielectric material. In fact, the material itself influences the propagation characteristics by increasing the value of the effective dielectric constant from 1, for air, to approximately 6, for silicon. In a line where ohmic losses are primarily responsible for loss performance, the other parameter that can further influence loss, for a given substrate, is the characteristic impedance. By increasing the characteristic impedance of the line, the current distribution on the conductors decreases, thus leading to less loss per guided wavelength.

It is known that the characteristic impedance of FGC lines strongly depends on its geometrical parameters including the center conductor width, the ground width, and their separation. For example, an effort to increase the characteristic impedance to values above 75 Ohms requires either a narrow conductor leading to current crowding, or wider aperture dimensions, leading to multimoding. To lower the line impedance without encountering the above problems, material can be removed under the line as previously demonstrated by [4] where the line is supported by Si bars periodically placed along the line, or by membranes [3,5]. While the use of membranes has demonstrated the lowest loss by a planar interconnect, they are limited by the need for backside processing, complexity of the layout, and the required size of the membrane. Herein, we present another approach which effectively removes material underneath the line without requiring suspension of the center conductor in free space.

In a line of coplanar type the field is very tightly concentrated in the aperture between the conductors. When material in this area is removed (see Figure 1), the line capacitance is reduced and leads to less current flowing in the conductors. As a result the line exhibits lower loss and lower parasitic capacitances, and reduces reflections at junctions. In the following sections, the development of these lines and their characterization in terms of loss will be presented and compared to the conventional FGC line. Furthermore, W-band bandpass filters realized in this geometry are characterized experimentally and their

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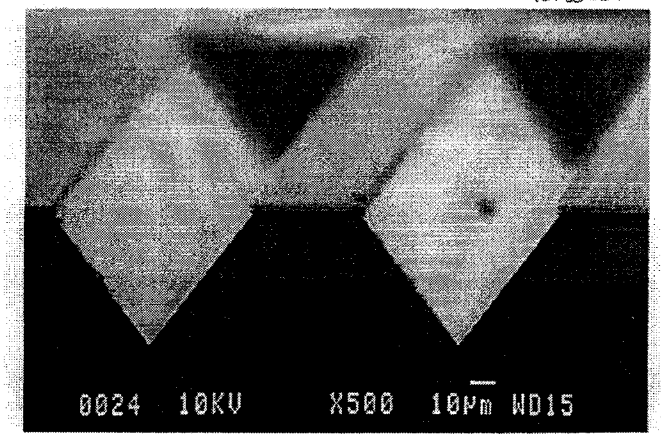

Figure 1. Scanning electron microscope (SEM) photo of anisotropically etched silicon grooves from 80 micron wide apertures on FGC line.

performance is compared to conventional ones to demonstrate superiority.

3.0 THE DEVELOPMENT OF MICROMACHINED FGC LINES

(a) Design of Micromachined Lines

Micromachined Finite Ground Coplanar (FGC) lines have a geometry similar to conventional FGC lines, except that the material underneath the line apertures has been removed, as shown in Figure 1. This structure has all the advantages of CPW including balanced propagation, coplanar configuration, and the capability of front-side wafer processing. In this particular line, the width of the line and the depth of the grooves provide direct control over the cut-off frequency of the next higher order mode and the range of single mode propagation. The groove size, G, can be defined as the aperture width (W) plus the lateral undercut. By appropriately choosing the ground-strip width (W_g), the signal-strip width (W) to separation (S) ratio, and the groove size (G), the cut-off frequency can be pushed beyond the upper frequency to be measured. The result is the elimination of the parasitic parallel plate/microstrip modes and the reduction of undesired loss. The design equation for this line is given below

$$2(W_g+S)+W = F_G\,\lambda_{o,h}/2$$

where $F_G = 1/(\sqrt{\varepsilon eff})$, a factor directly dependent to the amount of removed material. A plot of F_G versus undercut for five different aspect ratios is shown in Figure 2. Note that for each aperture width, the depth of the center of the V-shaped groove is dictated by the 53.7 degree angle of the <111> Si crystal planes. Therefore the 25 μm aperture yields a center depth of 17 μm, whereas that of the 80 μm aperture is 56 μm. In the limit of total dielectric removal, F_G goes to 1. However the initial value depends on the aspect ratio. As seen in Figure 2, the narrowness of the center conductor appears to have more influence than the width of the aperture. This indicates field confinement in the surface region, with little field penetrating deeply into the substrate. Due to the capability of the line to effectively confine the fields on one side of the wafer, wafer thickness and backside metallization are not critical to performance. As a result, wafer thinning is not required.

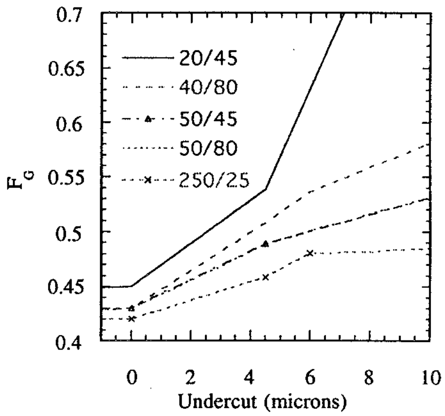

Figure 2. F_G vs Undercut (microns) for five different aspect ratios, W/S where W is the center conductor width and S is the aperture width.

Several micromachined FGC lines and filters circuits have been fabricated on 500 μm thick Si substrates. The total width of the line, $2(W_g+S)+W$, has been chosen for all designs to push the cut-off frequency of the first higher order mode to 120 GHz. The back side of the wafer is not metallized, but is in contact with a metal chuck during measurements. Since the realized geometries are symmetric, air-bridges for ground equalization are not included in the circuit. A number of similar structures of varying aspect ratio and groove size were designed for each type of passive component.

(b) Fabrication

As mentioned above, the micromachined FGC lines have been fabricated on 500 μm thick Si substrates with a 1.5 μm $SiO_2/Si_3N_4/SiO_2$ protective layer. After circuit metallization is obtained via electro-plating, Si apertures are opened and anisotropically etched using ethylene diamine pyrocatechol (EDP). Although both isotropic and anisotropic etchants have been investigated, anisotropic etching with EDP has been the most reliable. Since this selective etchant stops along the <111> crystal planes, this method of micromachining is relatively easy to control. Undercut at a rate of 2 to 3 µm per hour has been characterized and proven quite repeatable.

(c) Measurements

Following fabrication, S-parameters were measured using a Through-Reflect-Line (TRL) calibration. On-wafer calibration standards, consisting of micromachined FGC lines were used with NIST MultiCal software [6,7]. All measurements were made on an Alessi probe station using pico probes from 2 to 110 GHz, with a gap from 60 to 75 GHz, using several test sets. The resulting S-parameter data from the through and delay lines was then processed using MultiCal to compute the propagation constant, β, and attenuation constant, α.

4.0 Results

(a) Lines

Lines of various aspect ratios and groove sizes were fabricated and their loss was measured for frequencies varying from 2 GHz to 110 GHz. Measured results show that the loss strongly depends on the aspect ratio of the line and on the amount of material removed. Figure 3 shows loss in dB/mm for S-W-S lines of 45-20-45 microns for both conventional FGC and micromachined FGC with 4 micron undercut.

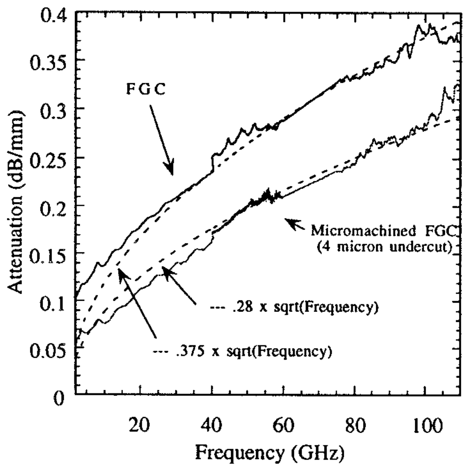

Figure 3. Attenuation vs. Frequency for FGC line with 20 µm center conductor and 45 µm apertures compared with micromachined line of same geometry.

The loss in the micromachined line is reduced by approximately 40% to 0.25 dB/mm at 94 GHz. The loss in dB/mm exhibits a square-root frequency dependence indicating dominance of conductor loss. Note this is in contrast to conventional microstrip and coplanar waveguide where dielectric in addition to radiation loss can increase the value of α to as high as 0.6-1 dB/mm.

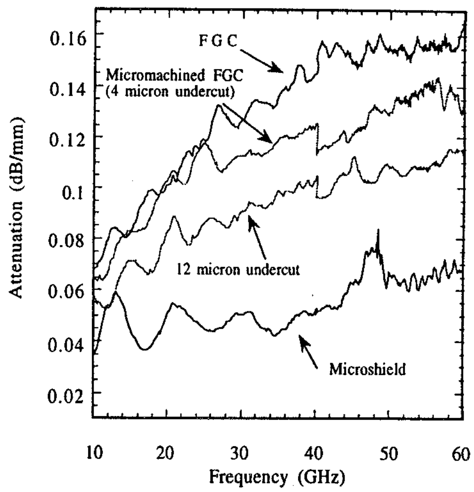

Figure 4. Attenuation vs. Frequency for 75 Ohm FGC line, micromachined FGC lines of same geometry, and a 75 Ohm microshield line.

Figure 4 shows the loss factor in dB/mm for a 80-40-80 µm micromachined line measured from 10 GHz to 60 GHz. The loss in this line has been reduced considerably to 0.115 dB/mm at 60 GHz. Since this loss is only ohmic and has a known frequency dependence, we can expect a value of 0.15 dB/mm at 94 GHz. Figure 5 shows the effective dielectric constant as a function of frequency for the conventional FGC and the micromachined lines with 4 and 12 micron undercut. The removal of the material results in reduction of the effective dielectric constant from the initial value of 5.6 to 2.7.

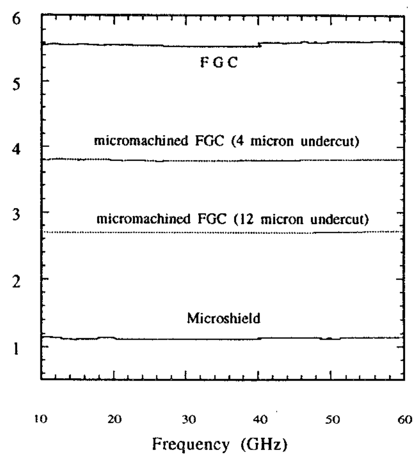

Figure 5. ε_{eff} vs Frequency for lines of Figure 4.

(b) W-Band-Bandpass Filter.

Micromachined lines with 45-50-45 and 80-50-80 μm geometries were utilized to develop four section bandpass filters. An example is shown in Figure 6. In this filter, Si was removed from the apertures as well as laterally for the interdigitated stubs to maintain structural integrity and avoid unwanted undercut at the corners. This filter was designed to have a 30% bandwidth and a center frequency of 94 GHz. The scattering parameters of this filter have been measured using a TRL calibration and the results are shown in Figure 7. The insertion loss of the filter at the center frequency is .8 dB and shows an improvement of .8 dB over the 1.6 dB insertion loss of a conventional FGC filter. The conventional filter had the same geometry, but was not micromachined. This micromachined FGC filter also shows excellent comparison with W-band microshield filters [8].

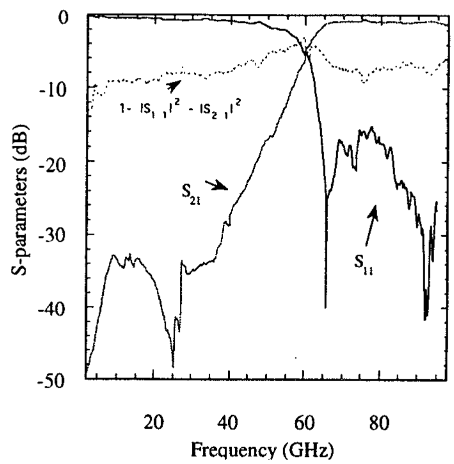

Figure 7. S-parameters of 4-section bandpass filter on micromachined FGC line.

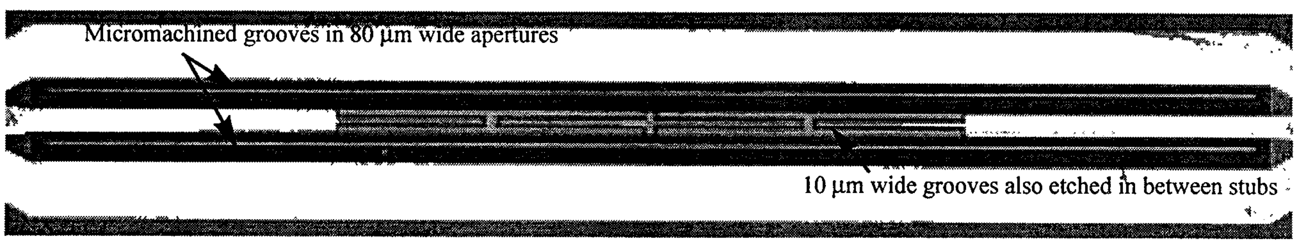

Figure 6. Micromachined FGC four-section bandpass filter.

5.0 CONCLUSION

It has been demonstrated that micromachined FGC line circuit elements offer much lower loss than conventional coplanar and FGC lines for frequencies as high as 110 GHz. By simply removing Si from the apertures, significant loss improvements can be made without sacrificing structural integrity and maintaining circuit dimensions. A micromachined bandpass filter has shown improved performance over a conventional FGC filter.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

[1] F. Brauchler, S. V. Robertson, J. East, L.P.B. Katehi, "W-Band Finite Ground Coplanar (FGC) Line Circuit Elements," in *1996 IEEE MTT-S Digest*, pp. 1845-1848.

[2] G. E. Ponchak, S. V. Robertson, F. Brauchler, J. East, L. P. B. Katehi, "Finite Width Coplanar Waveguide for Microwave and Millimeter-wave Integrated Circuits," *ISHM 1996 Proc. Int. Symp. on Microelectronics*, Minneapolis, Minnesota, pp. 517-521, Oct. 8-10, 1996.

[3] T.M. Weller, K.J. Herrick, and L.P.B. Katehi, "Quasi-Static Design Technique for Mm-Wave Micromachined Filters with Lumped Elements and Series Stubs," submitted to *IEEE MTT*, 1996.

[4] Katehi, L. P. B., "Novel Transmission Lines for the Submillimeter-wave Region," *Proceeding of the IEEE*, vol. 80, pp. 1771-87, Nov 92.

[5] T. M. Weller, L. P. B. Katehi, and G. M. Rebeiz, "High Performance Microshield Line Components," *IEEE MTT*, vol. 43, no. 3,pp.534-543, March 1995.

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

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

[8] S.V. Robertson, L.P.B. Katehi, and G.M. Rebeiz, "W-Band Microshield Low-Pass Filters," in *1994 IEEE MTT-S Digest*, pp. 635-628.

[9] D. F. Williams and S.E. Schwarz, "Reduction of Propagation Losses in Coplanar Waveguide," in 1984 *IEEE MTT-S Digest*, pp.453-454.