# Micro-fabricated Micro-coaxial Millimeter-wave Components

Zoya Popovic[1], Kenneth Vanhille[1,2], Negar Ehsan[1], Evan Cullens[1], Yuya Saito[1], Jean-Marc Rollin[2], Christopher Nichols[2], David Sherrer[2], Daniel Fontaine[3], Dejan Filipovic[1]
[1]University of Colorado, Boulder, CO 80309, [2]Rohm and Haas Electronics, [3]BAE Systems

***Abstract*—An overview of components designed and implemented in the PolyStrata micro-coaxial technology at millimeter-wave frequencies will be presented. The components are designed and characterized at the University of Colorado, and fabricated by Rohm and Haas Electronics, in collaboration with BAE Systems. Micro-coaxial air-filled cables with purely TEM propagation up to 450GHz are fabricated using sequential deposition of 5 to 11 layers of copper, and used to implement couplers, hybrids, Wilkinson dividers/combiners, impedance transformers, etc. from microwave frequencies to W band. Some advanced concepts for THz components are also achievable in this technology.**

## I. Introduction And Background

MICRO-coaxial lines with low loss enable millimeter-wave circuits with high density, extremely low coupling, and in some cases functionality that is not possible with planar guides such as microstrip or CPW. A coaxial line will support a pure TEM mode at millimeter-wave frequencies if its transverse dimensions are small (e.g. 1-mm commercial coaxial cables which are used to 110GHz). Such a line will have minimal loss if the dielectric is air, since in that case the capacitance in the attenuation constant low-loss line approximation, $\alpha \cong (R'/2)\sqrt{C'/L'}$, is minimized. This motivated development of wafer-scale micro-fabricated coaxial lines and components[1], as illustrated in Figure 1. The lines are fabricated using a sequential copper deposition process developed by Rohm and Haas Electronics[2]. The process results in demonstrated 5-layer and 11-layer lines, as shown in the SEM photographs in Figure 1. In addition to low loss and broadband TEM behavior, a wide range of impedances can be fabricated, resulting in a new library of components available to the circuit and system designer.

## II. Micro-Coaxial Transmission lines

Similar to surface micromachining techniques, the recta-coax structures are fabricated by depositing uniform layers (strata) of copper with aspect ratios on the order of 1 to 2 for layers that can be up to 150um thick. Once the structure is fabricated, the resist is drained through release holes in the top and side walls. The substrate is either low or high-resistivity silicon; however, other substrates may also be used. In the 5-layer and 11-layer coax cross-section depicted in Fig. 2a, a dielectric polymer supporting the center conductor is a part of the 3rd and 5th layer, respectively, and multiple dielectric supports may also be used. The heights of the 5-layer and 11-layer lines are approximately 300μm and 800μm, respectively.

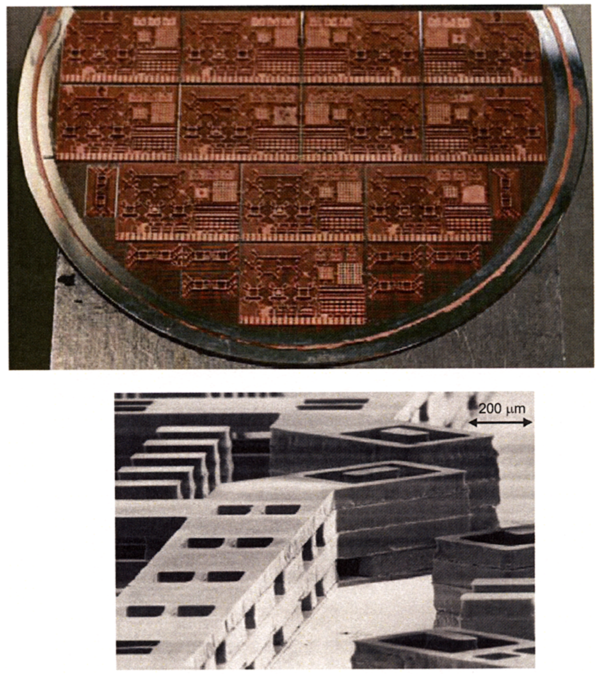


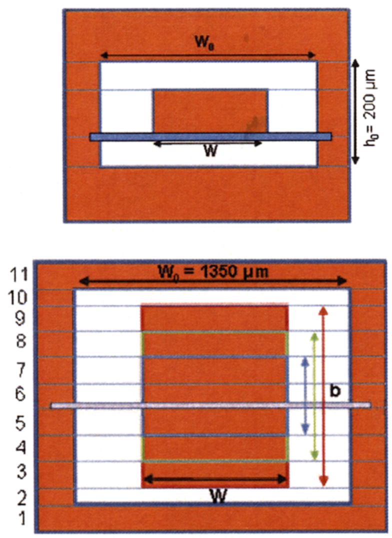

**Figure 1**. Photographs of a 6-inch wafer with copper micro-coaxial components, and SEM picture of a 5-layer line showing the release holes and metal strata.

The two coaxial lines in Figure 2a are different in several respects: the larger line takes longer to fabricate, but can handle more power and has a larger range of characteristic impedances. The possible range for a few geometric parameters is shown in Figure 2b, showing that lines with impedances from roughly 10 to 90Ω are possible with the same number of layers, i.e. on the same wafer.

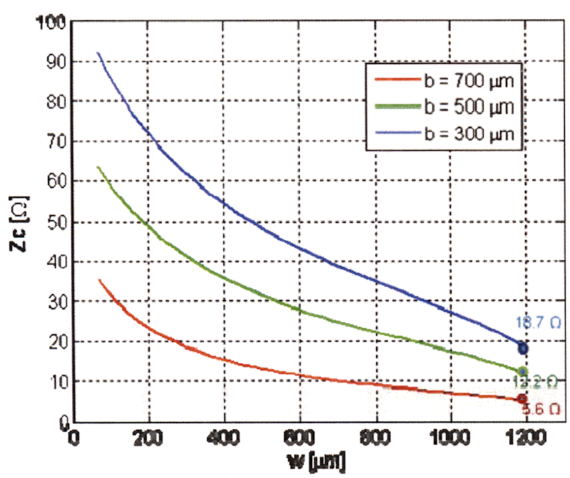
The two other properties of micro-coaxial lines that make them suitable for millimeter-wave and THz systems are the fact that the small size of the air-filled lines implies high-frequency purely TEM operation, and that the lines are shielded resulting in low coupling and high packing density. Figure 3 shows the comparison of previous results[3] to simulated cutoff frequency for the next higher order mode (TE10) in a 250-μm tall recta-coax cable as a function of characteristic impedance. The micro-coaxes are capable of supporting pure TEM propagation into the 0.5THz range, and higher for smaller dimensions, with losses limited by skin depth of the copper in this case.

978-1-4244-2120-6/08/$25.00 ©IEEE.

Low coupling between the lines enabled by the shielding of the outer conductor has been studied in detail4 and an example measurement in the microwave and lower millimeter-wave range is shown in Figure 4. The 4-port measurement shows below 60dB coupling between two coaxial lines with walls sharing a sidewall up to 50GHz, limited by the external SOLT calibration. These lines have demonstrated around 0.08dB/wavelength attenuation at 38GHz[1,5].




(a)




(b)

**Figure 2**. (a) Cross-section of a 5-layer (5-strata) and 11-strata micro-coaxial line. The top line is around 300um tall, while the 11-layer line is around 800um tall. (b) Calculated possible characteristic impedances of the lower line when the width of the inner and outer conductor is varied, while the layers are kept the same. The possible impedance range is from below 10 Ω to over 90 Ω.

## III. Micro-Coaxial Components

A variety of micro-coaxial millimeter-wave components have been demonstrated and published, e.g.: directional couplers[6], resonators[7,8], antennas[9], 90-degree hybrids[10], and Buttler matrices[1]. New components have recently been demonstrated at lower microwave frequencies with hybridly integrated surface mount elements: Wilkinson power dividers, inductors, impedance transformers, bias networks, transitions to CPW and connectors, and hybrid flip-chip active circuits.

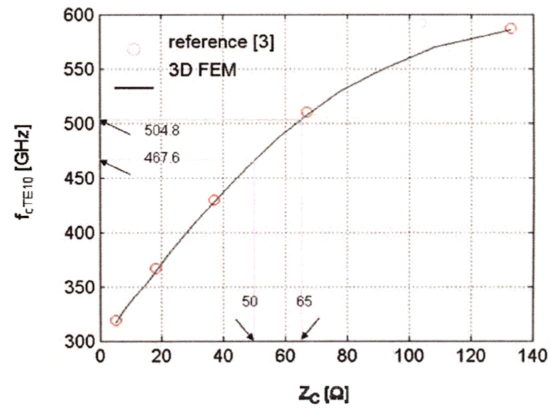



**Figure 3**. Simulated cutoff frequency of the first non-TEM mode in a 250-um tall micro-coaxial line, compared to calculations from the literature[3]. The line supports a pure TEM wave into the 0.5THz range.

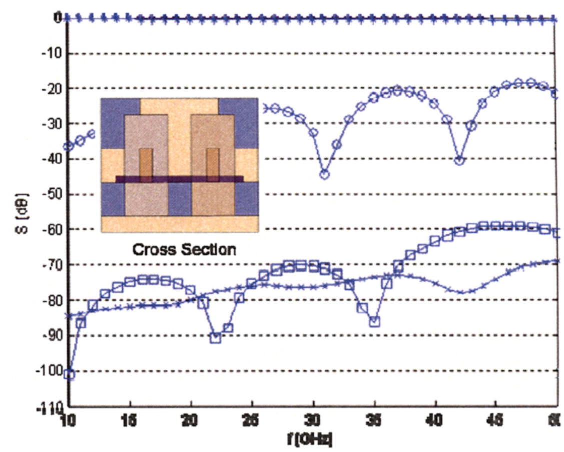



**Figure 4**. Simulated and measured 4-port s-parameters to 50GHz for two 250-um lines which share a side wall. The far-end coupling is below -70dB. Standing waves can be seen in the return loss (below -20dB) and near-end coupled line (below -60dB).

Some of the components and resulting performance are briefly discussed in the remainder of the paper, while details can be found in the corresponding references. Figure 5 shows a 10-dB coupled-line directional coupler which was successfully implemented in Polystrata™ technology with excellent agreement between simulation and measurement[6]. This coupler is relatively narrowband, as are a number of 90-degree hybrids that have been demonstrated in single and two-layer Polystrata versions[11]. Figure 6 shows a broadband micro-coaxial Lange coupler which covers the entire Ka band[12], as an illustration of what type of performance is possible in this broadband transmission medium.

978-1-4244-2120-6/08/$25.00 ©IEEE.

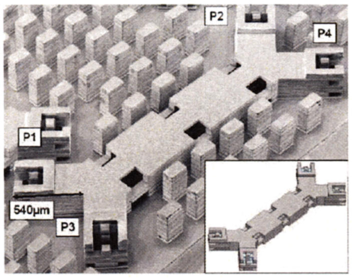
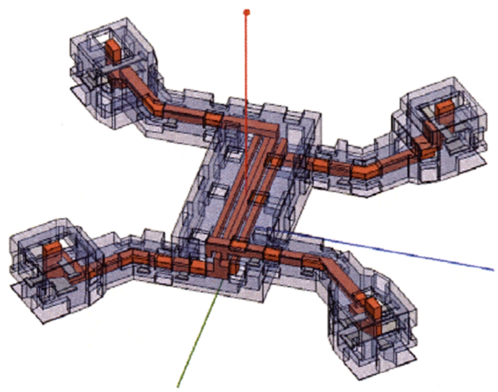
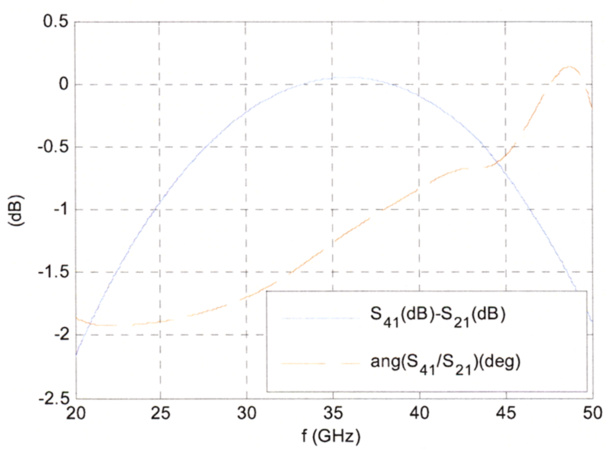



**Figure 5**. Photograph of a coupled-line directional coupler implemented in Polystrata with two coupled recta-coaxial lines.



(a)




(b)

**Figure 6.** Layout of a broadband 3-dB Lange coupler with an amplitude balance of 1dB between 25 and 47GHz, with a corresponding phase balance within 1.5 degrees[12].

ACKNOWLEDGMENTS

The authors acknowledge the help of Dr. Sebastien Rondineau, formerly at UC Boulder, Dr. Deepu Nair at Rohm and Haas and, Dr. Anthony Immorlica, Dr. Rick Thompson, Dr. Robert Actis and Gil Potvin from BAE Systems. The work was funded by the DARPA 3-D MERFS and DMT programs. Approved for Public Release, Distribution Unlimited, DARPA case #11814.

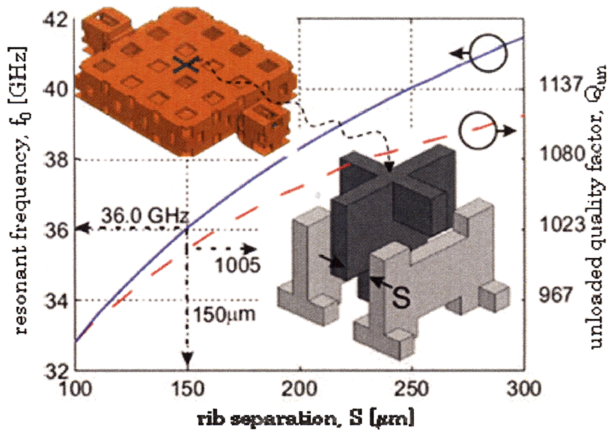



**Figure 7.** A 36-GHz miniaturized quasi-planar resonator with loading enables a Q factor of around 1000 in simulation, and around 900 in measurement[8,12].

REFERENCES

[1] D. Filipovic, Z. Popovic, K. Vanhille, M. Lukic, S. Rondineau, M. Buck, G. Potvin, D. Fontain, C. Nichols, D. Sherrer, S. Zhou, W. Houck, D. Fleming, E. Daniel, D. Wilkins, V. Sokolov, J. Evans, "Modeling, Design, Fabrication and Performance of Rectangular micro-Coaxial Lines and Components," *IEEE 2006 IMS Digest,* San Francisco, June '06.

[2] D. Sherrer, J. Fisher, "Coaxial waveguide microstructures and the method of formation thereof," U.S. Patent App.Publication No.US2004/0 263 290A1, Dec.30, 2004.

[3] L. Gruner, "Higher order modes in square coaxial lines," IEEE Trans. Microwave Theory Tech., vol. 31, no. 9, pp. 770-772, Sept. 1983.

[4] Y. Saito, D. S. Filipovic, *Analysis and Design of Monolithic Rectangular Coaxial Lines for Minimum Coupling*, IEEE Transaction on Microwave Theory and Techniques, pp. 2521-2530, Dec. 2007.

[5] M. Lukic, S. Rondineau, Z. Popovic, D. Filipovic, "Modeling of realistic rectangular micro-coaxial lines," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 5, pp. 2068-2076, May 2006.

[6] K. Vanhille, J. Rollin, S. Rondineau, J. O'Brien, J. Wood, S. Raman, Z. Popovic, "Ka-Band Surface-Mount Directional Coupler Fabricated using Micro-Rectangular Coaxial Transmission Lines," to be presented at the 2008 IEEE IMS Symposium, Atlanta, June 2008.

[7] K. Vanhille, D. Fontaine, C. Nichols, D. Filipovic, and Z. Popovic, "Quasi-planar high-Q millimeter wave resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 6, pp. 2439-2446, June 2006.

[8] K.Vanhille, D. Fontaine, C. Nichols, Z. Popovic, D. Filipovic, "Ka-band Miniaturized Quasi-Planar High-Q Resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 6, pp. 1272-1279, June 2007.

[9] M. Lukic, D. S. Filipovic, *Surface Micromachined, Dual Ka-band Cavity-Backed Patch Antenna*, IEEE Transaction on Antennas and Propagation, pp. 2107-2109, July 2007.

[10] K. Vanhille, J. Rollin, S. Rondineau, J. O'Brien, J. Wood, Z. Popovic, "Ka-Band Surface-Mount Directional Coupler Fabricated using Micro-Rectangular Coaxial Transmission Lines", *IEEE 2008 International Microwave Symposium Digest,* Atlanta, June 2008.

[11] K. Vanhille, D. Filipovic, C. Nichols, D. Fontaine, W. Wilkins, E. Daniel, and Z. Popovic, "Balanced low-loss Ka-band µ-coaxial hybrids," in *2007 Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, Honolulu, HI, U.S.A., June 2007.

[12] Kenneth Vanhille, *Design and Characterization of 3-D Millimeter-Wave Micro-fabricated Components,* Ph.D. Thesis Dissertation, University of Colorado, Boulder, June 2007.

978-1-4244-2120-6/08/$25.00 ©IEEE.