

# Micromechanical Sliding Planar Backshorts

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**Abstract**—A micromechanical tuning element which can be fabricated as an integral part of a planar transmission line, has been developed and demonstrated in a fully monolithic 620 GHz integrated circuit. The design of this integrated device, called a *sliding planar backshort (SPB)*, is based on a discrete SPB, previously demonstrated at 100 GHz. Its fabrication involves a unique application of sacrificial-layer and molding techniques, to materials and processes which are compatible with the fabrication of a wide range of MMIC's.

## I. INTRODUCTION

At millimeter and submillimeter wavelengths, the performance of common semiconducting and superconducting devices is severely degraded by the effects of parasitic reactances inherent in their geometries [1,2]. These effects are not easily characterized, and adjustable impedance matching circuits are typically needed to make practical use of such devices. A common approach is to embed the device in a waveguide circuit and employ mechanically adjustable waveguide backshorts as tuning elements which serve to optimize the device performance by compensating for the parasitic reactance [3]. The critical dimensions for these circuits are very small, decreasing in size as the frequency of interest increases. This makes fabrication of such waveguide circuits exceedingly costly and difficult, and has motivated interest in alternative planar approaches.

Monolithic integrated circuit technology promises a practical means for realizing reliable and reproducible planar millimeter and submillimeter wave circuits. Planar circuits are fabricated through photolithographic techniques, which allow for the cost-effective production of intricate designs not possible with waveguide technology. These circuits, however, must also provide compensation for parasitic device reactances. Conventional planar technology allows for only fixed tuning elements, providing no means for post-fabrication optimization of performance [4]. This makes characterization of the component elements critical, and it is not usually possible to achieve satisfactory results without multiple iterations.

An adjustable planar tuning element, which functions in a planar circuit analogously to a backshort in a waveguide circuit, has been developed, along with a process for its fabrication as an integral part of a submillimeter wave

monolithic circuit. It is called a *sliding planar backshort (SPB)*. It can be used in developmental circuits as an aid for device characterization, or as a means to optimize in-use performance for a variety of submillimeter wave integrated circuits.

## II. THE SLIDING PLANAR BACKSHORT

The SPB consists of a rectangular metal plate, with appropriately sized and spaced holes, which rests on top of a dielectric-coated planar transmission line, as shown in Fig. 1. The impedance of the sections of line covered by metal is greatly reduced, while the uncovered sections retain their higher impedance. Each of these sections is approximately one quarter-wavelength long, and the cascade of alternating low- and high-impedance sections results in an extremely low-impedance termination. This termination can be moved to vary the electrical length of a planar transmission line tuning stub, by simply sliding the metal plate along the length of the line. The semiempirical design of the SPB was carried out on a 2 GHz scale model [5], and the SPB has been successfully demonstrated as a discrete component at frequencies up to 100 GHz [6].

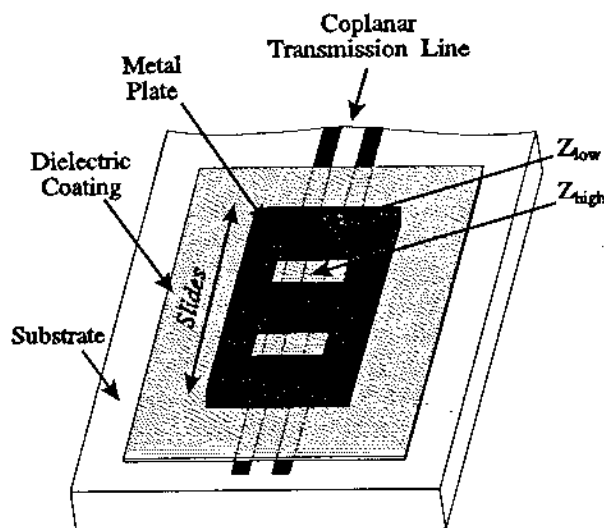


Fig. 1. Conceptual illustration of the SPB. A patterned metal plate slides over a dielectric-coated planar transmission line to vary the electrical length.

A quasi-optical, 620 GHz, direct-detection integrated circuit was developed to demonstrate the operation of an integrated SPB. This circuit used a dielectric-filled parabola to focus radiation onto a slot antenna, and coupled this radiation to a bismuth detector [7] by means of two coplanar waveguide (CPW) transmission lines, each with integrated SPB's. One SPB creates a variable reactance in series between the antenna and the detector, potentially serving to compensate for any unwanted reactance when the slot is not resonant. The other SPB creates a variable susceptance in parallel with the detector, and could be used to compensate for the parasitic capacitance found in some otherwise desirable submillimeter wave devices. The circuit is illustrated in Fig. 2.

The critical dimensions for the 620 GHz SPB, CPW lines, and dielectric-coating were scaled from an optimized 2 GHz model. The three conducting sections of the SPB each covered approximately  $80 \mu\text{m}$  of the CPW line, with a  $65 \mu\text{m}$  space after the first section and a  $75 \mu\text{m}$  space after the second. An additional space and conducting section was added to the micromechanical SPB to better facilitate its manipulation with a mechanical probe. The CPW line consisted of a  $16 \mu\text{m}$  wide center-conductor with  $8 \mu\text{m}$  gaps on either side. The appropriate thickness of the dielectric-coating was determined to be slightly less than  $1000 \text{ \AA}$  for silicon-dioxide at 620 GHz.

The photolithographic fabrication of microelectromechanical systems (MEMS) with submillimeter dimensions has been demonstrated, and is now a growing field with great potential [8]. Much of this work involves the fabrication of movable captivated structures by the *surface micromachining* of silicon. In this process a photopatterned polysilicon structure is deposited on a silicon substrate between two sacrificial oxide layers. A second photopatterned polysilicon structure is then deposited, overlapping the oxide-coated structure and anchoring to the substrate. The sacrificial oxide layers are then etched away, releasing the first polysilicon structure to move within the constraints of the second. A more recent MEMS fabrication

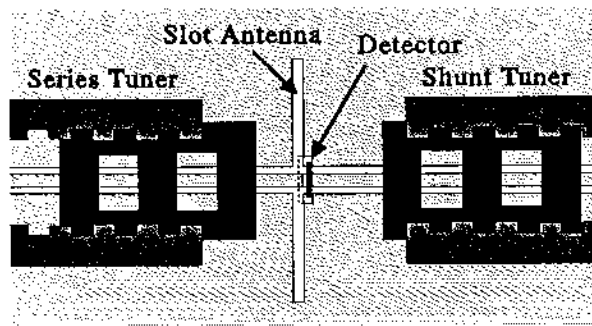


Fig. 2. The 620 GHz integrated circuit. Two micromechanical SPB's on dielectric-coated transmission lines form the adjustable impedance matching circuit.

technique, known as LIGA (a German acronym meaning lithography, plating and molding), allows for the fabrication of microstructures with larger vertical aspect ratios (over 100 to 1), and the use of materials other than silicon. This technique is used for the batch production of three-dimensional structures within a microfabricated cast or mold.

The dimensions for a 620 GHz SPB are comparable to that of common MEMS. However, neither of the techniques previously described can be used by itself as a practical means of fabricating a suitable SPB; some of the materials and processes involved are inappropriate for, or incompatible with, those often needed in a submillimeter wave circuit. Fortunately, key features from both techniques can be suitably combined in a process which allows for the fabrication of SPB's in a variety of submillimeter wave circuit applications.

### III. THE FABRICATION PROCESS

The procedure used for fabricating the micromechanical SPB's in the 620 GHz integrated circuit is illustrated in Fig. 3. The circuit was fabricated on a fused-quartz wafer, and the first two thin-film circuit layers,  $1000 \text{ \AA}$  of gold and  $1000 \text{ \AA}$  of silicon-dioxide, formed the dielectric-coated transmission line.

A photoresist lift-off stencil was applied, and photopat-

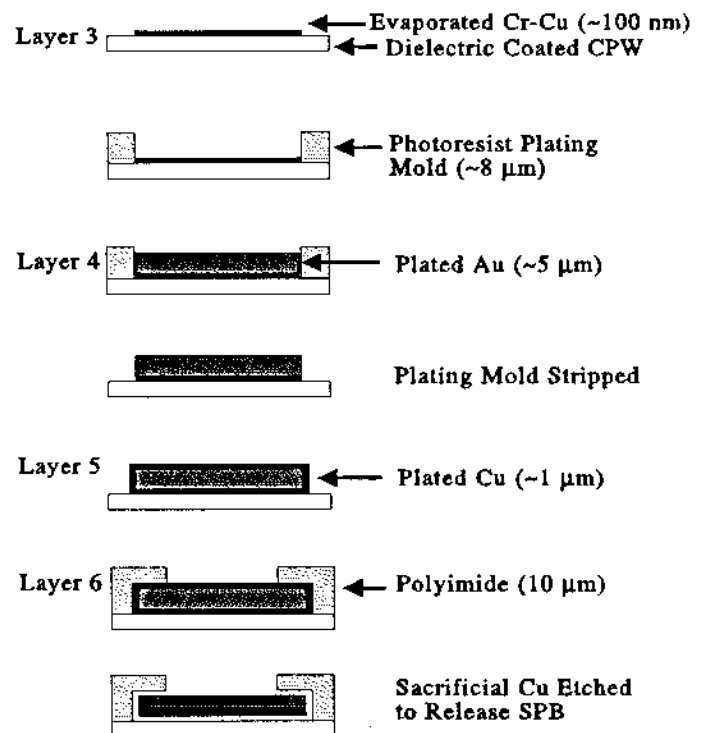


Fig. 3. Simplified illustration of the SPB fabrication process. Sacrificial layers are used to form an SPB which is constrained by guide-structures.

terned to define a sacrificial-seed layer. This pattern consisted of a rectangular strip over the coplanar lines, as wide as the SPB (200  $\mu\text{m}$ ) and extending to the edge of the substrate to allow for electrode connection. This third layer was formed by depositing a 1700  $\text{\AA}$  layer of copper over a 70  $\text{\AA}$  chrome adhesion layer through electron-beam evaporation, and then lifting the stencil and unwanted film in acetone.

Next, an 8  $\mu\text{m}$  layer of photoresist was applied to the circuit, patterned to form a mold layer, and hard-baked. This layer defined the shape of each SPB, several sacrificial pieces used to define the region into which each SPB would slide, and two 1mm<sup>2</sup> patches. These patterns were all formed over the sacrificial-seed layer to allow for electroplating, with the large square patches serving to increase the plating area and allow for the use of a maintainable plating current. The wafer was then dipped in gold electroplating solution where 5  $\mu\text{m}$ -thick patterned gold structures were plated within the mold, forming the fourth circuit layer.

The mold layer was then striped in N-methyl 2-pyrrolidone, and a 1  $\mu\text{m}$  sacrificial copper coating, Layer 5, was applied to the SPB's by connecting the circuit to an electrode and immersing it in copper electroplating solution. A 13  $\mu\text{m}$  layer of photosensitive polyimide-precursor was then spun onto the circuit, and patterned form two digitate strips, each overlapping one side the copper coated gold structures. The strips were then cured to form 9  $\mu\text{m}$ -thick polyimide guide-structures.

Finally, the copper plating and sacrificial-seed layers were removed in a wet etch, releasing the gold SPB structures to slide along the substrate within the polyimide guide-structure. An SEM of the circuit is shown in Fig. 4.

The illustration in Fig. 5 shows a close-up view of the guide structure with an SPB under it as fabricated (a), and as seen after sliding the SPB to another position (b).

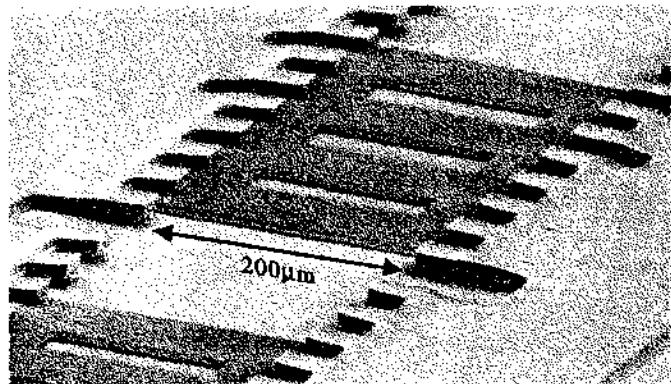


Fig. 4. SEM of the integrated circuit with with two SPB's. Each SPB controls the electrical length of a CPW line on either side of a slot antenna.

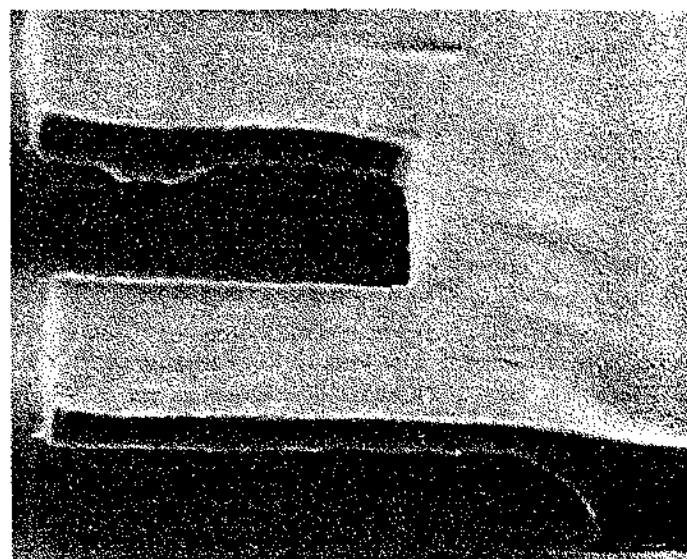
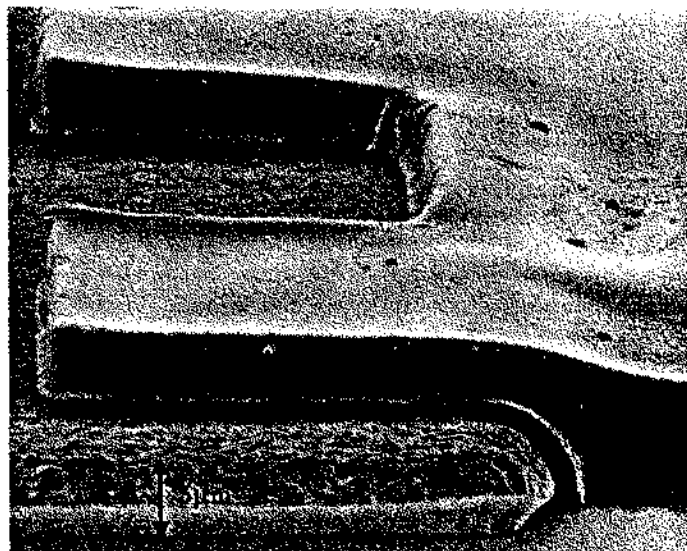


Fig. 5. Close-up SEM of one side of an SPB. The polyimide guide-structure is shown with (a) and without (b) the SPB beneath it.

#### IV. PERFORMANCE

The integrated circuit was completed by depositing a small rectangular patch of bismuth through evaporation and lift-off, and mounting the finished wafer over a substrate lens [9] to allow for quasi-optical performance measurements.

An theoretical model was derived for the 620 GHz integrated circuit and used to predict its performance. Impedances for the antenna (24  $\Omega$ ) and CPW lines (78  $\Omega$ ) were calculated [10,11] along with expected ohmic, dielectric, and radiative losses [12]. The measured value for the DC resistance of the bismuth detector (18.5  $\Omega$ ) was used, and measurements made using a 2 GHz scale model indicated that  $|s_{11}|$  should be -0.06 dB.

The performance of the integrated SPB's was demonstrated by using them to vary the power delivered from the slot antenna to the bismuth detector by altering the impedance match between them. The measurements were carried out at 620 GHz using a backward wave oscillator as a source, and the circuit response was successfully varied over a 15 dB range by manually positioning the SPB's with an ox-hair probe. The results for independent position sweeps for each SPB agreed very closely with theory.

#### V. ACKNOWLEDGEMENTS

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#### REFERENCES

- [1] I. Mehdi and P.H. Siegel, "Effect of Parasitic Capacitance on the performance of Planar Subharmonically Pumped Schottky Diode Mixers," *Fifth International Symposium on Space Terahertz Technology - Symposium Proceedings*, pp. 379-393, May 1994.
- [2] R. Blundell and C.-Y.E. Tong, "Submillimeter Receivers for Radio Astronomy," *Proceedings of the IEEE*, vol. 80, no. 11, pp. 1702-1720, November 1992.
- [3] M. Salez, P. Febvre, W.R. McGrath, B. Bumble, and H.G. Leduc, "An SIS Waveguide Heterodyne Receiver for 600 GHz-635 GHz," *International Journal of Infrared and Millimeter Waves*, vol. 15, no. 2, pp. 349-368, February 1994.
- [4] J. Zmuidzinas, H.G. Leduc, J.A. Stern, and S.R. Cypher, "Two Junction Tuning Circuits for Submillimeter SIS Mixers," *IEEE Trans. on Microwave Theory Tech.*, vol. 42, no. 4, pp. 698-706, April 1994.
- [5] V.M. Lubecke, W.R. McGrath, and D.B. Rutledge, "Sliding Backshorts for Planar Circuits," *International Journal of Infrared and Millimeter Waves*, vol. 12, no. 12, pp. 1387-1397, December 1991.
- [6] V.M. Lubecke, W.R. McGrath, and D.B. Rutledge, "A 100 GHz Coplanar Strip Circuit Tuned With a Sliding Planar Backshort," *IEEE*, vol. 3, no. 12, pp. 441-443, December 1993.
- [7] D.P. Neikirk and D.B. Rutledge, "Self-heated Thermocouples for Far-Infrared Detection," *Applied Physics Letters*, vol. 41, no. 5, pp. 400-402, September 1992.
- [8] J. Bryzek, K. Peterson, and W. McCully, "Micromachines on the March," *IEEE Spectrum*, pp. 20-31, May 1994.
- [9] P.H. Siegel and R.J. Dengler, "The Dielectric-Filled Parabola: a New Millimeter and Submillimeter Wavelength Receiver/Transmitter Front End," *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 1, pp. 40-47, January 1991.
- [10] G.V. Eleftheriades and G.M. Rebeiz, "Self and Mutual Admittance of Slot Antennas on a Dielectric Half-Space," *International Journal of Infrared and Millimeter Waves*, vol. 14, no. 10, October 1993.
- [11] K.C. Gupta, R. Garg, and I.J. Bahl, *Microstrip Lines and Slotlines*, Dedham, MA: Artech House, 1979.
- [12] M.Y. Frankel, S. Gupta, J.A. Valdmanis, and G.M. Mourou, "Terahertz Attenuation and Dispersion Characteristics of Coplanar Transmission Lines," *IEEE Trans. on Microwave Theory Tech.*, vol. 39, no. 6, pp. 910-916, June 1991.