FACTA UNIVERSITATIS (NIŠ)
Series: Electronics and Energetics vol. 8, No.2(1995), 287–298

MICROMECHANICAL PLANAR TUNING ELEMENTS

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Abstract. 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. Such circuits however, do not typically allow for post-fabrication optimization of performance, which can be a serious limitation. A mechanically adjustable planar tuning element suitable for integration in a variety of monolithic millimeter and submillimeter wave circuits has been developed. It is called a *sliding planar backshort* (SPB) and it can be fabricated as an integral part of a dielectric-coated coplanar transmission line. The SPB forms a movable RF short-circuit, which allows for the variation of the transmission line's electrical length. Measurements at 2 GHz have shown the return loss for the SPB to be better than -0.5 dB over a bandwidth of at least 50%, on various coplanar transmission lines. A photolithographically fabricated SPB has been demonstrated in a planar quasi-optical 100 GHz detector circuit in which the response of a Schottky diode was successfully varied over a range of almost 14 dB. A technique for fabricating a micromechanical version of the SPB has also been developed. Two such SPB's were fabricated as integral parts of a quasi-optical 620 GHz monolithic integrated detector circuit, and used to vary the measured response over a range of almost 15 dB. Such tuning elements can be used for characterizing developmental circuits, and for optimizing the in-use performance of various millimeter and submillimeter wave integrated circuits.

Manuscript received June 13, 1995. A version of this paper was presented at the second Conference Telecommunications in Modern Satellite and Cable Services, TELSIKS'95, October 1995, Niš, Yugoslavia.

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1. Introduction

The vast field of RF electronics has long capitalized on the advantages of simple and cost effective planar circuit technology. From 1 GHz to 40 GHz, microstrip, coplanar strip, coplanar waveguide, and slot transmission lines are commonly used for signal distribution in hybrid and monolithic circuits used in radar, communications, and remote sensing applications. Planar circuits have also shown great promise as an alternative to waveguide circuits in millimeter wave ($30-300$ GHz) and submillimeter wave ($300-3000$ GHz) applications. Typically, the transmission lines in these circuits are designed with a particular characteristic impedance, and some form of impedance transformation or tuning circuit is used to insure that the circuit components transfer the signal of interest along these lines in the most efficient way. Ideally, knowledge of the operating impedance of each component allows for a fixed circuit design which incorporates this impedance transformation. In practice, however, it is quite difficult to accurately characterize these components, particularly at high frequencies. As a result, some post fabrication tuning in the form of circuit modification is required. This type of tuning is not easy and it is required more often as the design frequency is increased. In the millimeter wave and submillimeter wave bands, it is usually not even possible.

It would therefore be advantageous to incorporate impedance matching elements into planar circuits which can be readily fine tuned after fabrication in order to relax the constraint of component characterization, and thus allow the circuit design to be extended to higher frequencies. In waveguide circuits, this tuning is accomplished with a mechanically adjustable backshort which is inserted into the waveguide [1]. This provides a tuning stub with an adjustable electrical length. Waveguide, however, is often difficult to interface with planar components, and as the frequency of interest increases, the physical dimensions of the waveguide decrease and make the waveguide circuit difficult and costly to fabricate through conventional machining techniques.

Alternatively, planar circuits are fabricated photolithographically, making them more simple and cost-effective to manufacture, and allowing for the production of circuits which are more complex than those which can be fabricated in waveguide form [2]. A new tuning element has been developed which functions in a planar circuit analogously to an insertable backshort in a waveguide circuit. It is called a *sliding planar backshort* (SPB) and it can be used to mechanically vary the electrical length of a coplanar transmission line tuning stub. The SPB thus allows for the design of planar RF circuits which can be actively tuned after fabrication, providing compensation for any device or circuit variations in order to achieve optimal performance. The SPB is a planar structure with physical dimensions on the order of a wavelength for the design frequency. This allows it to be photolithographically fabricated using the same techniques used for the rest of the planar circuit. Additionally, a technique has been developed which allows for the fabrication of a micromechanical SPB as an integral component in a monolithic submillimeter wave integrated circuit.

2. Design of the SPB

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.

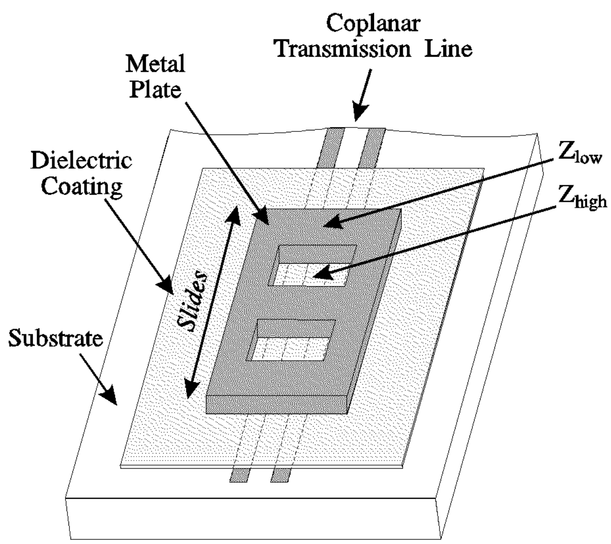


Fig. 1. Conceptual illustration of the SPB. A patterned metal plate slides over a dielectric-coated planar transmission line to vary the electrical length

A $2GHz$ large-scale circuit was first used to demonstrate the function of the SPB, and to allow for the empirical optimization of its design [3]. The circuit shown in Fig. 2 was constructed to allow the reflection coefficiant for the SPB to be monitored with an HP8510 over a $5GHz$ frequency range. The performance of the SPB was optimized by systematically varying the length of the low- and high-impedance sections, the number of sections, the dimensions of the transmission line, and the thickness of the insulator in order to achieve the largest reflection of RF power.

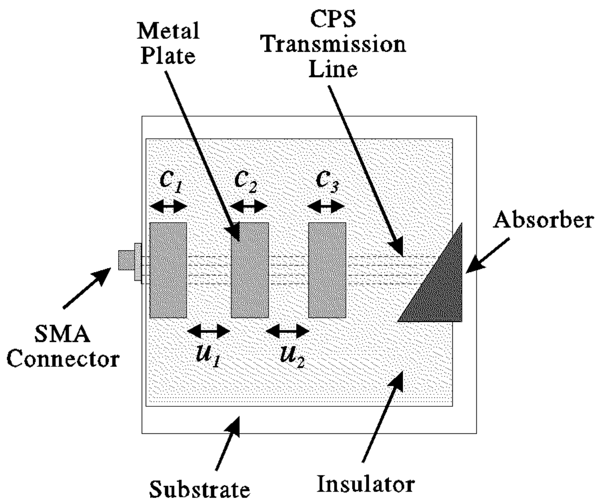


Fig. 2. Circuit used for optimizing the SPB. The dimensions of the metal plates, transmission lines, and various insulators were varied to optimize the performance of the structure as a backshort.

Good performance over a useful bandwidth was obtained for a coplanar transmission line with two $2.1mm$ wide copper strips, separated by a $5.2mm$ gap and mounted on a $6mm$ thick Stycast substrate with a dielectric constant of $\epsilon_{re} = 4$. The characteristic impedance and effective dielectric constant of this transmission line were determined to be 203Ω, and 2.4, respectively [4]. A $25\mu m$ thick sheet of Mylar ($\epsilon_r^i \approx 2.9$) was used to insulate the transmission line from the sliding plate. This noncontacting, $76mm$ wide, $6mm$ thick aluminum plate contained two rectangular holes with dimensions and spacing of $c_1 = 24.3mm$, $u_1 = 19.4mm$, $c_2 = 24.0mm$, $u_2 = 23.0mm$, and $c_3 = 24.4mm$. This resulted in uncovered high impedance sections, u_1 and u_2, and

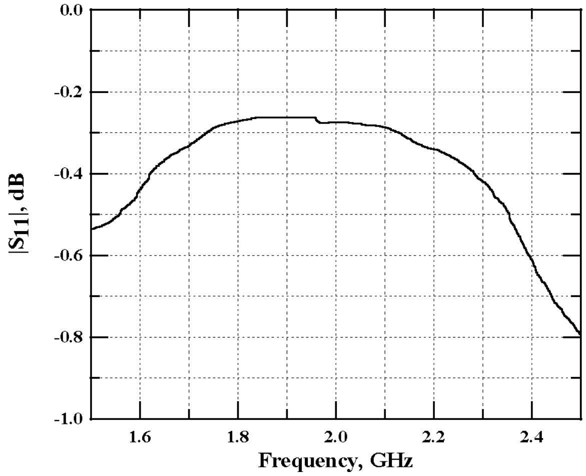


Fig. 3. Performance of the optimized SPB on 90Ω *coplanar strip transmission line. The reflection coefficient,* $| s_{11} |$, *is better than* -0.3 *dB over a* 20% *bandwidth*

covered low impedance sections, c_1, c_2 and c_3, which were each approximately $\lambda_g/4$ long on the coplanar line.

A plot of $| S_{11} |$ versus frequency is shown in Fig. 3. This optimized planar backshort produced an $| s_{11} |$ better than $-0.3\ dB$ over a 20% bandwidth. That is, a reflection of more than 90% of the power in the incident wave. The center frequency was measured to be 2 GHz, which agrees exactly with the design frequency. A measurement comparing the performance of the metal plate SPB to that of a one inch thick block of Stycast backed by similarly patterned copper tape, was also made using this technique and yielded almost identical results for both.

The performance of the optimized metal plate SPB was also tested on a CPW transmission line which was the physical compliment of the optimized CPS transmission line. The impedance was calculated as 78Ω [4]. The measured result for $| s_{11} |$ is shown in Fig. 4. The peak return loss was $| s_{11} |= -0.02\ dB$ at 2.1 GHz, and $| s_{11} |$ was less than 0.5 dB over a 50% bandwidth.

3. Millimeter Wave Implementation

A means of implementing a photolithographically fabricated SPB in a planar millimeter wave circuit was devised. The performance of the sliding short was tested in a 100 GHz detector circuit which utilized a design derived from an existing 230 GHz planar heterodyne receiver [5].

The quasi-optical circuit utilized a dielectric-filled parabola as a sub-

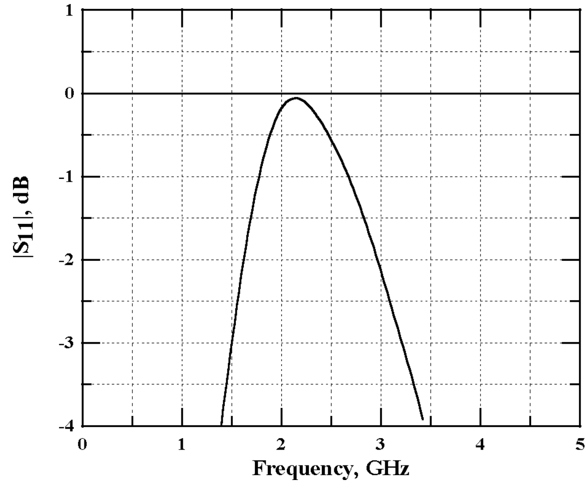


Fig. 4. Plot of the reflection coefficient for the SPB on 78ω coplanar waveguide transmission line.

strate lens, serving to focus incident RF radiation onto a planar dipole antenna. A GaAs Schottky beam-lead diode mounted across the antenna was used as a detector with DC bias and detector output carried by a coplanar strip transmission line. The antenna circuit was fabricated as a thin-film gold pattern on a quartz wafer, coated with a thin dielectric layer (polyimide), and mounted over the substrate lens. The SPB was fabricated as a thin-film silver pattern on a movable superstrate which could be placed metal-side-down on the antenna circuit. The SPB thus acts as an RF termination on the coplanar strip transmission line, forming a planar tuning stub whose electrical length can be varied to compensate for parasitic reactance in the diode. This allows for the adjustment of the impedance match between antenna and detector to optimize the circuit's performance. The circuit is illustrated in Fig. 5.

Measurements were made with the detector circuit illuminated by a modulated 100 GHz source. The detected power, measured with a lock-in amplifier, was recorded with the sliding short manually positioned at various distances, d in Fig. 5, along the transmission line. Measurements were made using two sliding short designs, both having identical dimensions along the transmission line, but one with a wider metallization pattern across the line. Detected power, normalized to the response with no SPB present ($\simeq 160\mu v$), is shown in Fig. 6 as a function of the SPB position, normalized to th guide wavelength for the coplanar strip transmission line (λ_g).

A theoretical model was developed for this circuit and the predicted

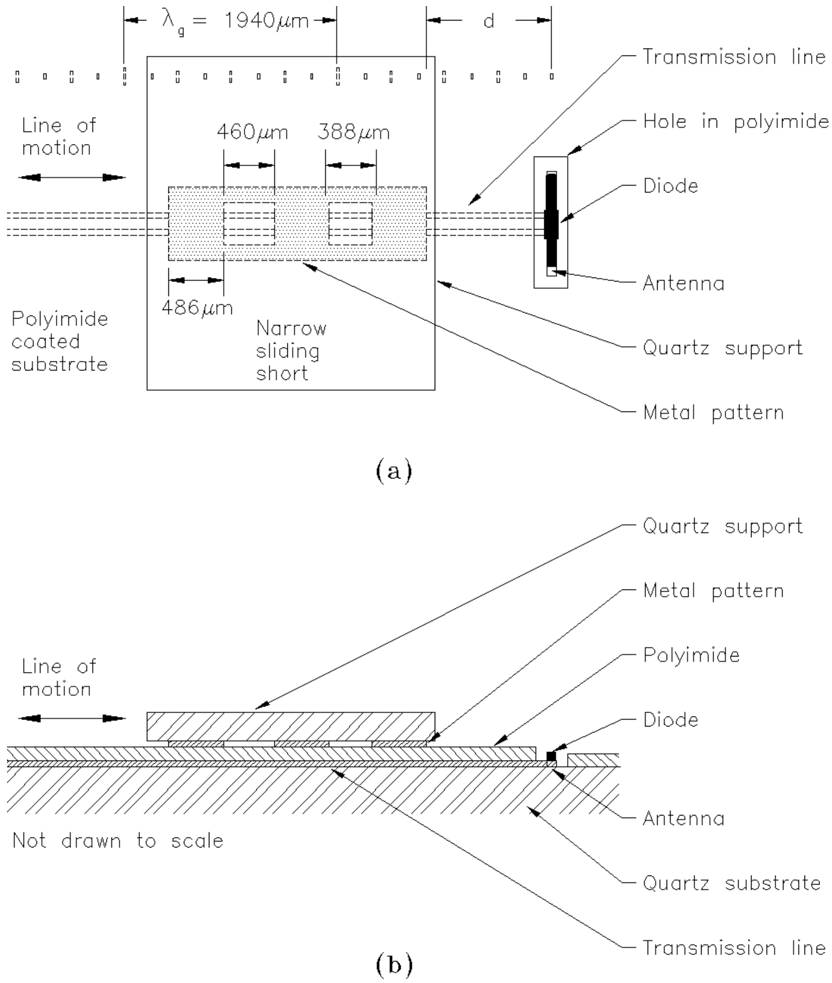


Fig. 5. Top view (a) and cross section (b) of the mechanically tunable planar detector circuit. The SPB is moved along the transmission line to provide an adjustable impedance in parallel with the diodel

performance is also shown in Fig. 6. The model includes calculations for both ohmic and radiation losses for the 190Ω coplanar strip transmission line and uses $\mid s_{11} \mid = -0.3\ dB$ for the SPB, as measured in the 2 GHz experiment. A parasitic coupling effect between the SPB and antenna was also observed. An attempt was made to measure this coupling and the effect was added to the theoretical response; this is also shown in Fig. 6.

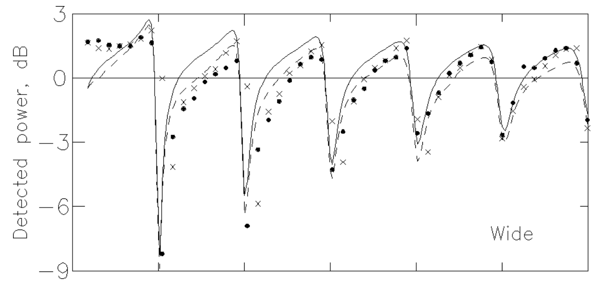


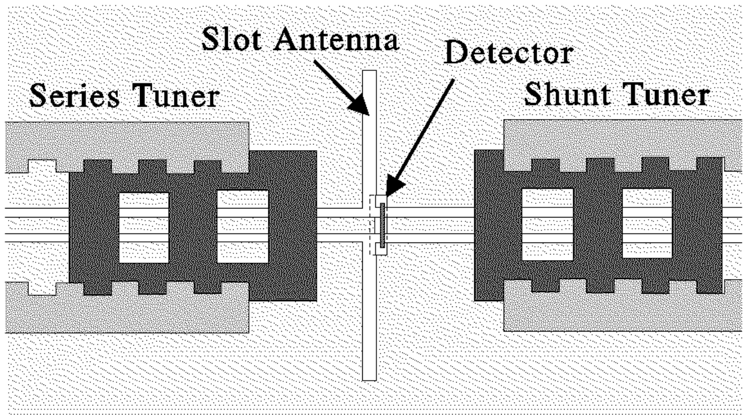
Fig. 6. Data for two typical trials (•) (×) is shown for both the wide (a) and narrow (b) SPB's. Theory is shown both without (−), and with (- -) the coupling effect included

4. Submillimeter Wave Integration

A quasi-optical, 620 GHz, direct-detection integrated circuit was developed to demonstrate the operation of an integrated SPB [6]. 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. 7.

The critical dimensions for the 620 GHz SPB, CPW lines, and dielectric-coating were scaled from the optimized 2 GHz model. The three conducting sections of the SPB each covered approximately$80\mu m$ of the CPW line, with a $65\mu m$ space after the first section and a $75\mu m$ 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 $16\mu m$ wide center-conductor with $8\mu m$ gaps on either side. The appropriate thickness of the dielectric-coating was determined to be slightly less than $1000\mathring{A}$ 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 photopat-



Fig, 7. The 620GHz integrated circuit. Two micromechanical SPB's on dielectric-coated transmission lines form the adjustable impedance matching circuit

terned 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 technique, known as LIGA (a German acronym meaning litography, 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.

The fabrication process used for the SPB's in this monolithic submillimeter wave integrated circuit is outlined in Fig. 8. The entire circuit was fabricated on a fused-quartz wafer, and the first two thin-film circuit layers, $1000\mathring{A}$ of gold and $1000\mathring{A}$ of silicon-dioxide, formed the antenna and the dielectric-coated transmission line on which the SPB's would function.

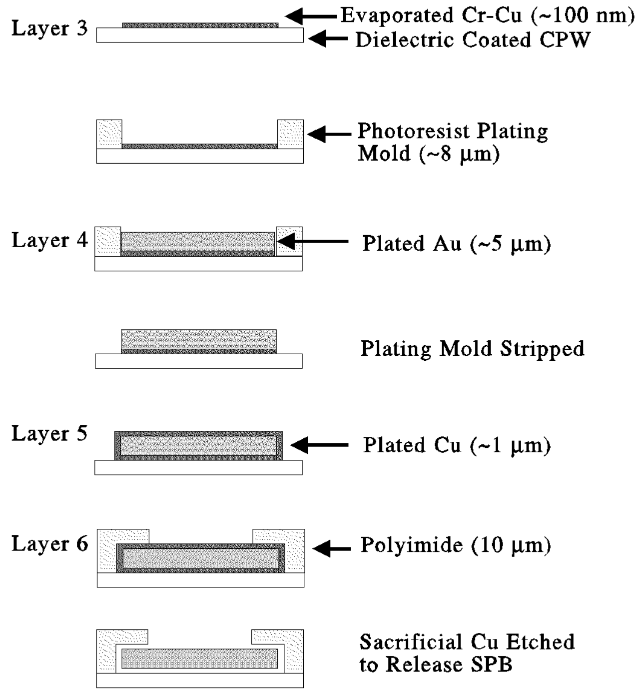


Fig. 8. Simplified illustration of the SPB fabrication process. Sacrificial layers are used to form an SPB which is constrained by guide-structures

A sacrificial-seed layer was then applied by photopatterning a thin-film (1000$\mathring{A}$ layer of copper as a rectangular strip over the transmission lines. This was followed by the deposition of a thick ($8\mu m$) layer of photoresist, patterned to form a mold for the SPB's. The gold SPB structures were then formed by electroplating ($5\mu m$) onto the sacrificial-seed layer, within the openings in the mold. The photoresist was then removed, and a thin sacrificial layer of copper ($1\mu m$) was electroplated over the SPB and seed layer. A thick layer of photosensitive polyimide ($10\mu m$) was then patterned to form two guide-strips which overwlapped two sides of each SPB, and anchored to the substrate. Finally, the sacrificial copper was removed through wet etching, allowing the gold SPB structures to slide freely within the constraints of the polyimide guide-strips. An SEM of the two SPB's is shown in Fig. 9.

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 (24Ω) and CPW lines (78Ω) were calculated [9,4] along with expected ohmic, dielectric, and radiative losses [4,10]. The measured value for the DC resistance of the bismuth detector (18.5ω) 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.

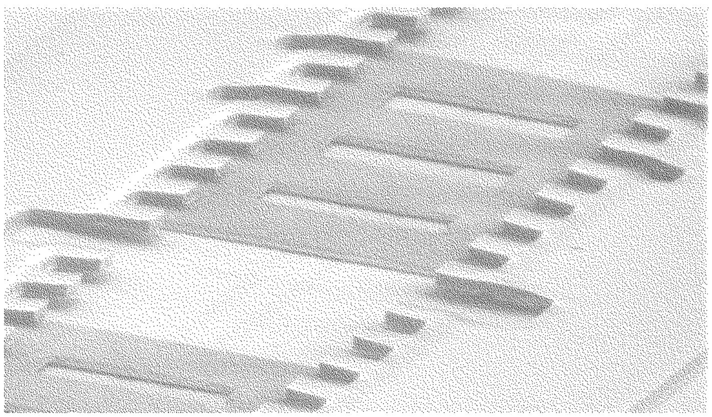


Fig. 9. SEM of the integrated circuit with with two SPB's. Each SPB controls the electrical length of a CPW on either side of a slot antenna

5. Acknowledgements

The authors would like to thank Dr. P.A. Stimson and Prof. Y.-C. Tai for their generous assistance. The research described in this paper was sponsored by NASA in the form of a Graduate Student Researchers Program fellowship as well as a contract provided through the Jet Propulsion Laboratory.

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