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ADJUSTABLE TUNING FOR PLANAR MILLIMETER-WAVE CIRCUITS

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At millimeter wavelengths uncontrollable parasitics are often large enough to significantly degrade circuit performance when they are not compensated by adjustable elements. It is difficult to add adjustable elements to planar millimeter-wave circuits without increasing their size, weight, and cost. In this paper we investigate three adjustable elements, all involving movement of a short along a section of coplanar waveguide (CPW). These tuners are incorporated in a planar detector circuit for purposes of demonstration and characterization. Their losses are determined. The precision with which they can be adjusted is also considered. Of the three, a tuner based on the laser-assisted etching of molybdenum is shown to have the highest performance at millimeter wavelengths. This tuner employs laser direct write etching[1] with a recently developed photochemical reaction for trimming molybdenum.

Key words: Integrated circuit, laser etching, coplanar waveguide, adjustable backshort.

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Introduction

As frequency increases it becomes more difficult to obtain high performance from electronic circuits without the use of adjustable elements. This is a well known problem of planar millimeter-wave integrated-circuit technology, where uncontrollable parasitics are often large enough to significantly degrade circuit performance. It is possible to adjust a millimeter-wave integrated circuit by coupling it to a section of rectangular metal waveguide and then using standard methods of waveguide tuning to obtain an adjustable reactance, or by adjusting the distance between the planar circuit and a metal conductor suspended above it.[2,3] It is usually desirable to avoid such large mechanically adjustable elements, however, because of the added fabrication cost and the increase in size and weight of the integrated circuit.

In this paper we investigate three tuning methods suitable for use with millimeter-wave integrated circuits, all of which involve movement of a short along a section of coplanar waveguide (CPW). The electrical length of the CPW section is changed, and hence its reactance. This variable reactance may be used to cancel the effect of a parasitic reactance in the circuit by placing the two elements in series or in shunt with one another. Advantages of the integrated circuit are not lost when these tuning methods are employed, since the non-planar structures used to modify the length of the CPW are removed after the circuit is tuned. The losses and settability (the smallest increment with which the position of the short may be varied along the length of the CPW tuner) of these tuners are low enough to be suitable for use at millimeter wavelengths. A planar detector circuit has been used for demonstration at 33 GHz.

CPW Tuners

The first type of tuner, which we shall call the "strip tuner", makes use of a sequence of closely-spaced shorting strips, which can be removed one at a time to vary the position of the short. The strips are all fabricated simultaneously by the photolithographic process described in Table 1. The structure is shaped like a railroad track, the "ties" being the shorting strips. The "rails" play no role electrically, but serve to keep the shorting strips parallel and evenly spaced. The strips are thermo-compression bonded to the CPW. Since the "rails" and the thermo-compression bonds are both easily broken, the shorting strips can be removed one at a time mechanically without damaging the underlying conductors which compose the CPW. This changes the electrical length of the shorted CPW section. (One might think of using wire bonds for this purpose. However, the spacing between the conductors of CPW at millimeter wavelengths is very small. As a result, bonds made with a conventional bonding machine turn out to be much higher than they are wide, leading to problems of non-uniformity and excessive radiation. It is also difficult to obtain the small, uniform bond wire separations necessary at millimeter wavelengths.)

Step	Description
1.1	Clean wafers
1.2	Evaporate 450 Å of chrome and 2000 Å of gold
1.3	Apply and pattern AZ 4330 photoresist
1.4	Descum resist
1.5	Plate 20 μm of gold
1.6	Remove resist
1.7	Ion mill Gold and Chromium
1.8	Etch Chromium and lift off pattern

Table 1. The process steps used to fabricate the gold shorting strips.

The second tuner, called the "solder tuner", is illustrated in Fig. 2. Here the CPW section is coated with a layer of indium solder. A gold plate (also coated with a layer of indium solder) is held by a hot vacuum mount and lowered on a micrometer stage until it comes into contact with the layer of solder on the CPW section. The liquid solder then provides a good electrical contact between the conductors of the CPW section and the gold plate. The plate is free to slide over the CPW conductors which varies the position of the backshort. During the adjustment process the operation of the circuit can be continuously monitored. After the short has been adjusted to the desired position, the heat is turned off, the solder solidifies, and the cool vacuum mount is removed. Only the soldered gold plate is left on the circuit. It is found that the vacuum mount does not influence the circuit's operation significantly if precautions are taken to cool the semiconductor devices mounted on the circuit. Thus the circuit remains optimized when the soldering apparatus is removed.

The third tuner, called the "laser-etched tuner", is illustrated in Fig. 3. A layer of molybdenum is sputtered over the gold CPW conductors, shorting them together. The position of the short is changed by placing the circuit in a 200 torr flowing chlorine atmosphere and locally heating the molybdenum layer with a focused argon-ion laser beam. This stimulates the formation of volatile molybdenum chlorides which are carried away in the flowing chlorine atmosphere. The result is that the molybdenum is etched away, leaving the underlying gold CPW conductors intact. Scanning the beam across the guide successively exposes more of the CPW below the molybdenum layer, changing the effective position of the molybdenum short along the length of the CPW section. Etching is induced both pyrolytically and photochemically; at the incident power of ≈ 600 milliwatts employed in this experiment, both mechanisms are important.[4] For these

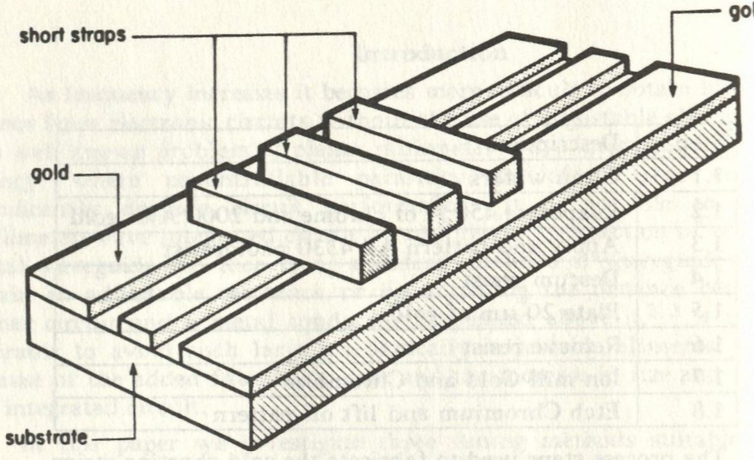

Fig. 1. Strip tuner in coplanar waveguide (CPW). The shorting strips are removed mechanically one at a time. This changes the effective position of the backshort, and hence, the admittance of the tuner.

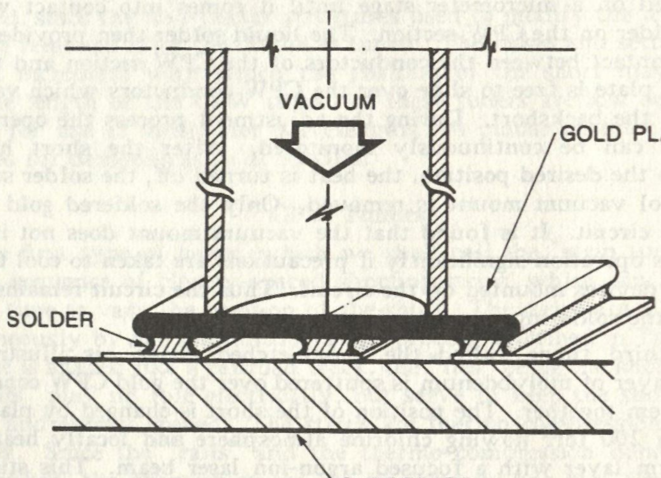

Fig. 2. Solder tuner in coplanar waveguide (CPW). The molten solder forms the electrical contact between the conductors of the CPW and the gold plate, shorting together the CPW conductors. The gold plate slides over the CPW conductors on the layer of molten solder. This changes the position of the short formed by the gold plate, and hence, the admittance of the tuner.

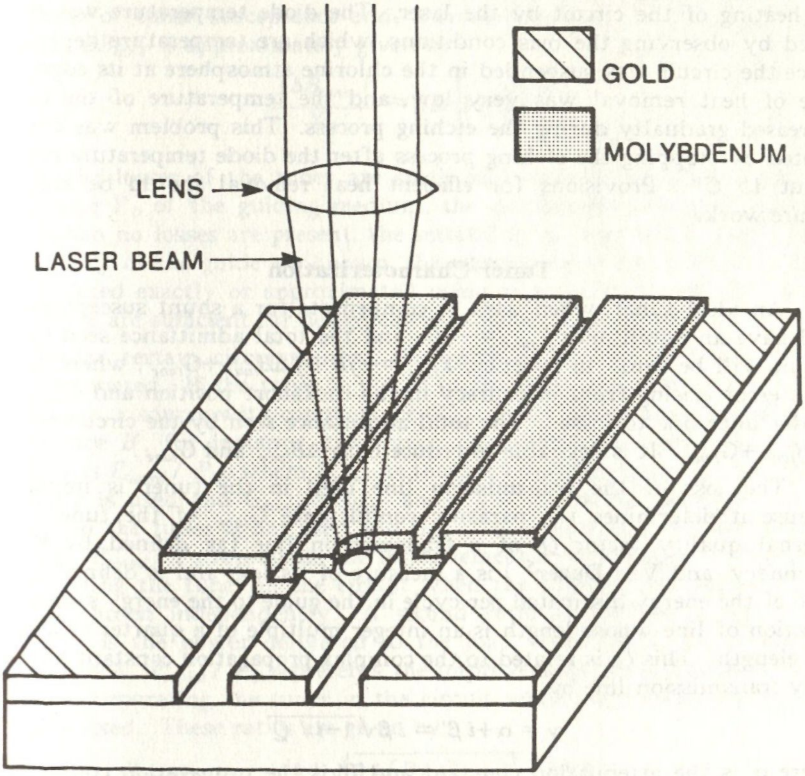

Fig. 3. Laser etched tuner in coplanar waveguide (CPW). The laser stimulates a local chemical reaction which etches away the molybdenum film shorting the gold CPW conductors. The effective position of the backshort is changed by moving the substrate forward slowly as the beam is scanned from side to side, progressively etching the molybdenum film away and exposing the gold CPW conductors underneath. This changes the position of the short formed by the remaining molybdenum, and hence, the admittance of the tuner. Submicron spatial resolution can be achieved permitting continuous tuning to with high precision. The laser etching is performed in situ as the device is exercised at millimeter-wave frequencies.

experiments, the laser beam was focused to a 2 μm spot size and scanned at a rate of 250 $\mu m/sec$. The distance between scans was set to 1 μm. The only undesirable effect of the laser etching process on the circuit was caused by heating of the circuit by the laser. The diode temperature was monitored by observing the bias conditions, which are temperature dependent. Since the circuit was suspended in the chlorine atmosphere at its edges, the rate of heat removal was very low, and the temperature of the circuit increased gradually during the etching process. This problem was circumvented by stopping the etching process after the diode temperature rose by about 15 C^o. Provisions for efficient heat removal should be made in future work.

Tuner Characterization

An ideal tuner, when used to compensate for a shunt susceptance B, will have an admittance $Y_{tune} = -jB$, and the total admittance seen by the circuit will be zero. In practice, $Y_{tune} = -jB + j\Delta B_{tune} + G_{tune}$, where ΔB_{tune} is an error arising from inaccuracy in the backshort position and G_{tune} is a conductance due to losses. The total admittance seen by the circuit is thus $j\Delta B_{tune} + G_{tune}$. It is desirable to reduce both ΔB_{tune} and G_{tune}.

The loss of the transmission line used in the tuner is important because it determines the parasitic conductance G_{tune} of the tuner. The internal quality factor Q of a transmission line (as defined by Ramo, Whinnery, and Van Duzer[5]) is a measure of its loss and is defined as the ratio of the energy dissipated per cycle in the guide to the energy stored, for a section of line whose length is an integer multiple of a quarter of a guide wavelength. This Q is related to the complex propagation constant γ of the lossy transmission line by

$$\gamma = \alpha + i\beta' = i\beta\sqrt{1 - i/Q} \tag{1}$$

where α is the attenuation constant and β' is the propagation constant of the lossy transmission line and β is the propagation constant of the lossless transmission line. For the usual case where $Q \gg 1$, β and β' are approximately equal, and the Q may be related to the attenuation constant by

$$Q \cong \frac{\beta}{2\alpha} \tag{2}$$

The Q, as defined here, is dependent only on the intrinsic loss of the guide. The shunt conductance G_{tune} of the tuner is approximately given by[6]

$$\frac{G_{tune}}{Y_0} \approx \frac{1}{2Q}\left|\beta l\left[1 + \frac{B^2}{Y^2_0}\right] + \frac{B}{Y_0}\right| \tag{3}$$

where B is the susceptance to be tuned, $Q \gg 1$, Y_0 is the characteristic admittance of the transmission line of which the tuner is composed, and $B / Y_0 \lesssim 1$.

The settability Δl of the backshort is the smallest increment with which the position of the backshort may be adjusted. It is an important characteristic of the tuner because it determines the smallest achievable increment of tuner susceptance and, therefore, ΔB_{tune}. If $B / Y_0 \lesssim 1$, the quantity ΔB_{tune} is approximately given by[6]

$$\frac{|\Delta B_{tune}|}{Y_0} \approx \beta \Delta l \left| 1 + \frac{B^2}{Y_0} \right| \tag{4}$$

If the losses of the tuner are small and resistive in nature, and the admittance Y_0 of the guiding medium, the propagation constant β of the guide when no losses are present, the settability Δl, and the internal quality factor Q of the guide are known, the admittance of the tuner Y_{tune} may be calculated exactly or approximated using equations (3) and (4). These parameters are sufficient for design calculations.

Under certain circumstances, the performance of the tuner can be easily estimated. If the tuner is placed in shunt with a load with conductance G_{load}, a source with conductance G_{source}, and a parasitic element with susceptance B, for instance, two ratios of interest are easily calculated. The first is P_{tuned} / P_0, where P_{tuned} is the power delivered to the load when the tuner is used and $G_{source} = G_{load}$ and P_0 is the power delivered to the load when the tuner is not used and G_{source} is chosen for maximum power transfer. P_{tuned} / P_0 represents the improvement in performance possible by incorporating the tuner in the circuit when the source conductance G_{source} may be chosen independently. A second ratio of interest is P_{tuned} / P_1, where P_1 is the power delivered to the load when $G_{source} = G_{load}$ and no tuner is used. P_{tuned} / P_1 represents the improvement in performance possible by incorporating the tuner in the circuit when the source conductance G_{source} is fixed. These ratios are given by

$$\frac{P_{tuned}}{P_0} = e_{tune} \frac{(1+\sqrt{1+(B / G_{load})^2}\,)^2 + (B / G_{load})^2}{4\sqrt{1+(B / G_{load})^2}} \tag{5}$$

$$\frac{P_{tuned}}{P_1} = e_{tune} (1 + (B / 2G_{load})^2) \tag{6}$$

where e_{tune}, the proportion of the available power delivered to the load when the tuner is in use, is given by

$$e_{tune} = \frac{1}{(1+G_{tune} / 2G_{load})^2 + (\Delta B_{tune} / 2G_{load})^2} \tag{7}$$

Detector Circuit

The three tuners described above were incorporated in the planar detector circuit shown in Fig. 4. Incident radiation is received by the slot

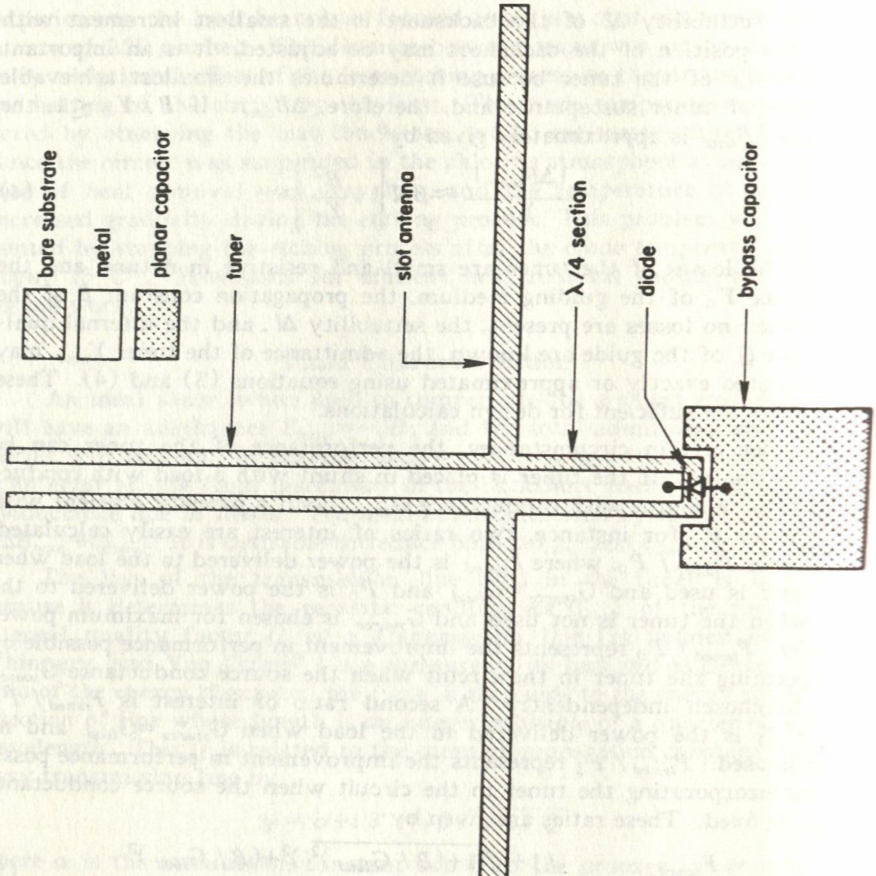

Fig. 4. Tunable detector circuit. The incident radiation creates a voltage across the slot antenna. The diode is placed at the end of the (approximately) quarter-wavelength CPW section. This transformer matches the slot impedance to the incremental resistance of the diode. The length of the tuner is adjusted to compensate for the parasitic diode capacitance.

antenna shown in the figure. A quarter-wavelength section matches the antenna impedance (about $3.3\,\Omega$) to the impedance of a silicon beam-lead diode biased to an incremental resistance of $418\,\Omega$. The CPW tuner is then used to compensate for the parasitic shunt capacitance of the diode. The CPW had a characteristic impedance of $50\ \Omega$, a total width of $296\ \mu$m, and a center conductor width of $148\ \mu$m. (The total width of the CPW was made about half the usual size to reduce radiation, which is difficult to model, although this results in additional ohmic loss.) The circuit was fabricated on a sapphire wafer. The fabrication process has been described earlier.[7]

The detected signal was measured as a function of the position of the backshort for the three tuners discussed above. Since the silicon diode has a rather high capacitance for use at 33 GHz, the improvement in performance over the untuned case ($l=0$ of Fig. 4) is quite significant. The model shown in Fig. 5 represents the detector circuit. The model parameters C_p, R_s, and C_j were obtained from the manufacturer of the diodes (Metelics Corp type MSS 40,141-B10, for which $C_j=0.20pF$ and $R_s=5\,\Omega$, were used for the strip and solder tuners and type MSS 40,140-B10, for which $C_j=0.05pF$, and $R_s=13\,\Omega$, for the laser-etched tuner). The value of C_p used in the model (.05 pF) was chosen to fit the observations. This value is larger than the .03 pF specified by the manufacturer; the difference probably arises from placing the diodes over the dielectric substrate. The incremental resistance of the diode is a function of both the bias conditions and the temperature, and was $418\ \Omega$ for the strip tuner, $428\ \Omega$ for the laser-etched tuner, and $525.6\ \Omega$ for the solder tuner (which was operated at a significantly higher temperature). All of the other parameters of the model (except the Q of the CPW lines and the value of L_p) were derived from low frequency measurements of scale models. The value of L_{ext} was determined from scale model measurements to be 0.020 nh for the laser-etched tuner and 0.015 nh for the strip and solder tuners; the difference being due to the different thicknesses of the 5000Å molybdenum film and the $20\ \mu$m shorting straps and gold plates.

The Q of the transmission lines in the actual circuit were estimated by fitting the tuning curves generated from the equivalent circuit to the measured tuning curves shown in Figs. 6-8. The Q and the value of L_p were considered to be adjustable parameters of the model. The value of L_p was considered to be adjustable because it depends both on the method of installation and on the diode type. The shape of the curve was quite sensitive to L_p; this allowed us to estimate the value of L_p. The values of L_p which gave the best fit to the experimental data shown in Fig. 6-8 were .11 nh, .11 nh, and .04 nh respectively. Then the Q was determined by comparing the measured and calculated ratios of $V_{det}(\beta l_{max})/\ V_{det}(\beta l=0)$, where $V_{det}(\beta l)$ is the voltage response of the diode when the length of the tuner is l. $V_{det}(\beta l_{max})$ was the voltage response when the device was tuned for maximum responsivity and $V_{det}(\beta l=0)$ is the voltage response of the

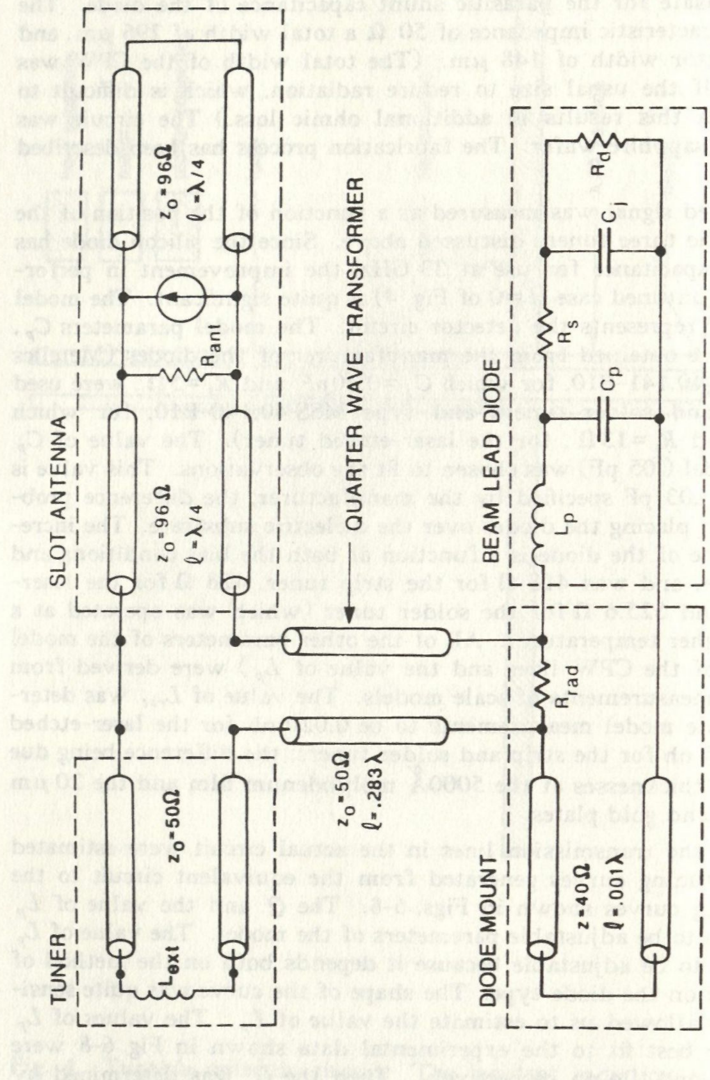

Fig. 5. The model used to analyze the detector of Fig. 4. The circuit values are $R_{ant} = 696\,\Omega$, $R_d = 417\,\Omega$, $R_{rad} = 4000\,\Omega$. The other circuit values are given in the text.

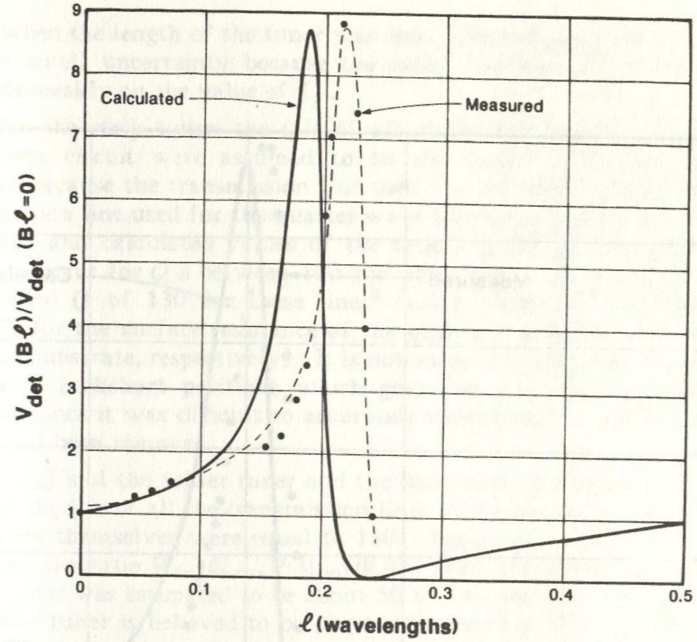

Fig. 6. The measured and calculated responses of the detector utilizing the strip tuner as a function of backshort position.

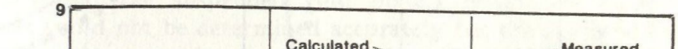

Fig. 7. The measured and calculated responses of the detector utilizing the solder tuner as a function of backshort position.

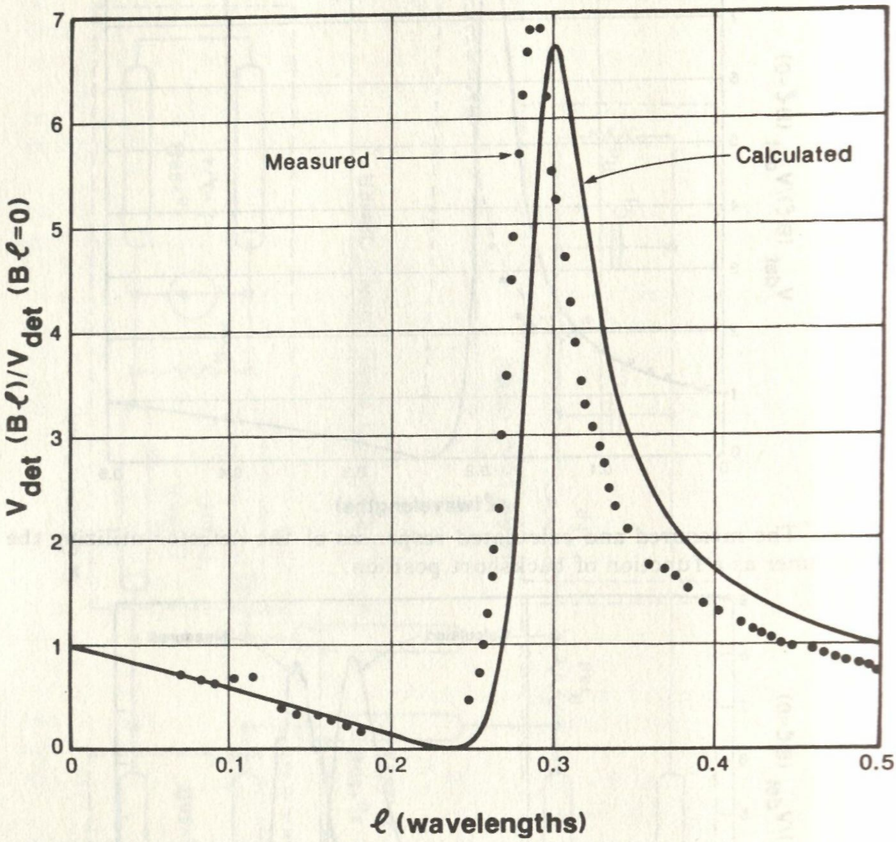

Fig. 8. The measured and calculated responses of the detector utilizing the laser-etched tuner as a function of backshort position.

diode when the length of the tuner was zero. The resulting value of Q contains a small uncertainty because the ratio $V_{det}(\beta l_{max})/\ V_{det}(\beta l=0)$ also depends weakly on the value of L_p.

For the strip tuner, the Q's of all of the transmission lines in the equivalent circuit were assumed to be the same. (This assumption is justified because the transmission line used for the tuner is identical to the transmission line used for the quarter wave transformer.) Agreement of the measured and calculated values of the ratio $V_{det}(\beta l_{max})/\ V_{det}(\beta l=0)$ was found to occur for Q's between 100 and 150. This is to be compared with a predicted Q of 130 for these lines[8] (using values of $0.0535\,\Omega/\square$ and $1x\ 10^{-4}$, for the surface resistance of the gold film and loss tangent of the sapphire substrate, respectively). It is not surprising that the measured and calculated backshort positions which gave the maximum response were different since it was difficult to accurately determine the number of strips which had been removed.

The Q's of the solder tuner and the laser tuner were found by assuming that the Q's of all the transmission lines in the equivalent circuit except the tuners themselves were equal to 130. Again, calculated and measured values of the ratio $V_{det}(\beta l_{max})/\ V_{det}(\beta l=0)$ were compared. The Q of the solder tuner was estimated to be about 50 by this method. The lower Q of the solder tuner is believed to be due to the presence of flux. (An attempt was made to tune the detector circuit in a nitrogen atmosphere without using flux, but the solder did not form a good contact between the waveguide and the suspended gold plate.) Again, the position of the backshort could not be determined accurately for the solder tuner, and the calculated and measured curves do not show the same position of the maxima.

Molybdenum Backshort

The Q of the laser-etched tuner was estimated by the above procedure to be about 130. Within the accuracy of the technique, this is the same as that estimated for the strip tuner. In this case, the device was mounted on a computer controlled stage, and the position of the backshort could be determined very accurately. The measured and calculated curves are in very close agreement.

The molybdenum film used in the laser-etched tuner backshort has a resistivity of about four times that of gold and was less than half as thick as the layer forming the gold CPW conductors. It seems curious that the Q of the of the laser-etched tuner should be about the same as that of the strip tuner, since the 5000Å thick molybdenum backshort might be expected to be quite resistive.

To solve for the impedance Z of a molybdenum backshort a complicated boundary value problem must be solved.[9] It is possible, however, to estimate the impedance of the backshort easily in the two limits of either very high or very low loss. In the limit of very high loss, the backshort may be modeled as a CPW transmission line shunted by the lossy molybdenum layer. In this limit the impedance Z of the backshort has equal real and imaginary parts. As the surface resistance of the molybdenum film becomes smaller, this model predicts that the impedance of the backshort approaches zero.

In the limit of very low loss, the impedance of the backshort becomes purely inductive because the short has some external inductance. In this case, the impedance of a planar CPW backshort becomes $Z \cong j\omega L_{ext}$, where L_{ext} is the external inductance of the backshort. This is not consistent with the transmission line model of the lossy backshort, which fails for highly conductive films, and predicts that Z has equal real and imaginary parts and that the absolute value of Z approaches zero as the resistivity of the molybdenum approaches zero.

In general, both limits must be considered, since both the resistive loss of the molybdenum and the external inductance contribute to current penetration into the backshort. The farther the currents penetrate into the conductor, the lower the resistance of the backshort. Since both effects increase current penetration, the actual resistance of the backshort is lower than that predicted by either model, and the models can be considered to give upper bounds on the resistance of the backshort. After exploring these two limits, we will show that for our case the estimated backshort resistance is consistent with the low measured loss of the laser-etched tuner.

Under the assumption of high loss, the resistance of the molybdenum backshort is estimated by modeling it as a lossy transmission line with a shunt conductance per unit length G given by

$$G = \frac{2t}{\rho_{moly} w} \tag{8}$$

where t is the thickness of the film, w is the width of the slots in the CPW, and $\rho_{moly} = 5.78x10^{-6}\,\Omega$ cm is the resistivity of molybdenum. (The factor of two in equation (8) is a result of there being two slots shorted by the molybdenum in shunt across the transmission line. The skin depth does not enter since in this case it is greater than t, the thickness of the molybdenum. If the skin depth of the molybdenum were less than t, G would become complex.) The characteristic impedance Z of the backshort is then given by[5]

$$Z = \sqrt{j\omega L / (G + j\omega C)} \tag{9}$$

and the propagation constant γ by

$$\gamma = \sqrt{j\omega L (G + j\omega C)} \tag{10}$$

where L is the inductance of the line per unit length, C is the capacitance of the line per unit length, and ω is the angular frequency. (The values of L and C are most easily found by looking up the quasi-static values for Z

and γ in tables[10] and solving for L and C under the assumption that G is zero. Then the actual values of Z and γ are found from L, C, and G.) For our backshorts (with $t = 5000\text{Å}$, $w = 75\mu m$, $\epsilon_r = 10.5$, and a quasi-static impedance of 50Ω), $Z = (1+j)0.4\Omega$ and the wave decays to its $1/e$ point in a distance $d_{lossy} = 11\mu m$. This 0.4Ω resistance is large enough to have reduced the measured Q to approximately 50.

Rosa gives a formula for the external inductance of a thin perfectly conducting strip[11, 12]

$$L_{ext} \approx 2w_{ind}\left(\ln(2\pi w_{ind}/d_{ind}) - 1 + d_{ind}/w_{ind}\pi\right)\ nh \tag{11}$$

where d_{ind} is the width of the strip and w_{ind} is the length of the strip in cm. Under the assumption of low loss, the molybdenum backshort may be modeled as two strips of length w_{ind} approximately equal to the width of the slots between the CPW conductors and width d_{ind}, where d_{ind} must still be determined. Physically, the quantity d_{ind} corresponds approximately to the depth of current penetration into the backshort. The external inductance L_{ext} of a low loss backshort may be measured at low frequency. The quantity d_{ind} may be estimated by setting the inductance calculated from equation (11) equal to the external inductance measured at low frequency. The resistance of the backshort may be estimated from d_{ind}, the approximate depth to which the currents penetrate into the molybdenum conductor, to be $Z \approx w\,\rho_{moly}/(2d_{ind}t)$. For our backshort, for which $L_{ext} \approx 0.02$ nh and $w_{ind} \approx 90\mu m$ (w_{ind} is chosen to be slightly larger than w, the width of the slots, since the currents must travel around the ends of the short), $d_{ind} \approx 25\mu m$, which is considerably larger than d_{lossy}. From this we conclude that the currents penetrate much farther into the backshort than would be expected in the lossy model. This implies the surprising (and fortuitous) result that, because of the current spreading due to the external inductance of the backshort, the resistance of the backshort is on the order of only one tenth of an ohm, which is small compared to the ohmic conductor loss of the CPW section.

Conclusion

The Q due to ohmic loss is proportional to the width of the CPW, which was only half of the usual width, so the Q of these tuners could easily be doubled by doubling the width of the guide. Since the Q of the guide is dominated by ohmic loss, the expected Q as a function of frequency of these wider lines (based on skin depth formulas[5]), is

$$Q \approx 1494/\sqrt{f} \tag{12}$$

for the strip and laser-etched tuners and

$$Q \approx 689/\sqrt{f} \tag{13}$$

for the solder tuner where f is the frequency in GHz and the dielectric constant of the substrate is equal to 10.5. The settability of the strip and

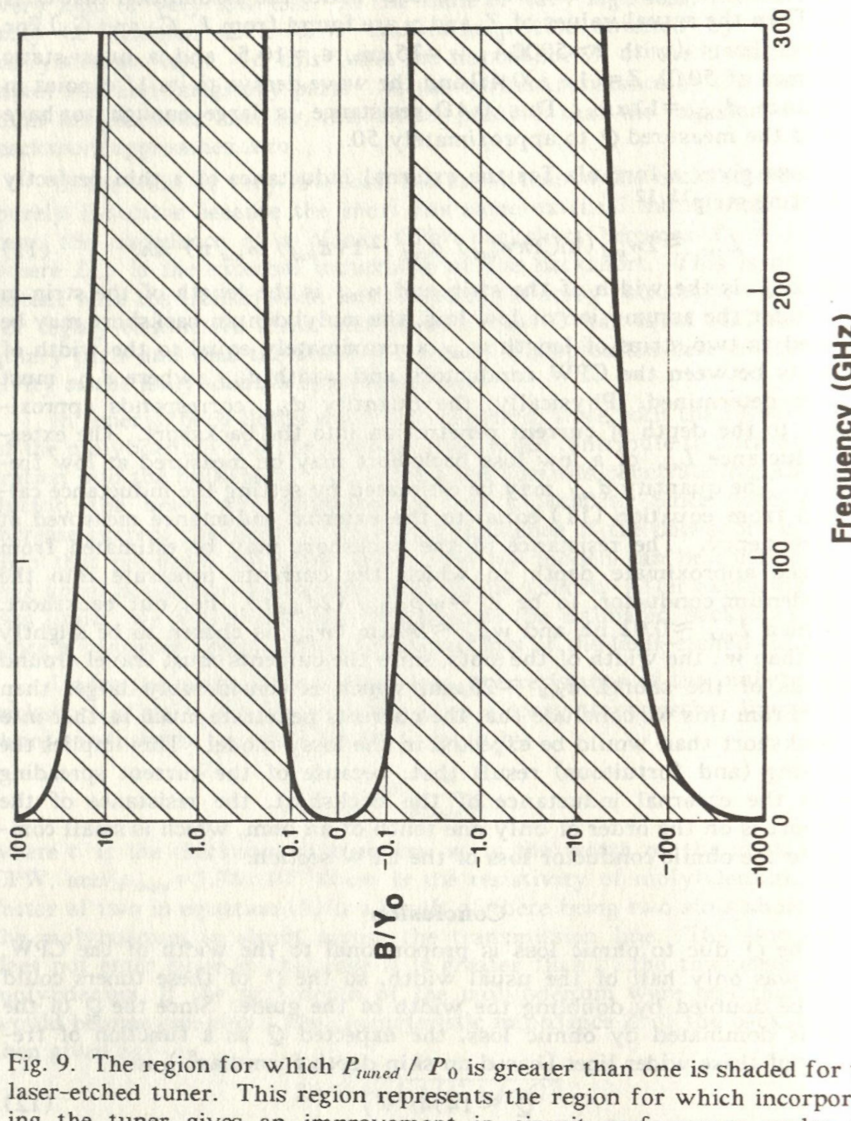

Fig. 9. The region for which P_{tuned} / P_0 is greater than one is shaded for the laser-etched tuner. This region represents the region for which incorporating the tuner gives an improvement in circuit performance under the assumptions stated in the article and the source conductance may be chosen independently. The Q of the tuner is assumed to be given by equation (12) and the settability of the tuner is assumed to be 1 μm.

solder tuners was about 32 μm. This value could easily be reduced by a factor of 3 if improvements in the positioning apparatus were made. The settability of the laser-etched tuner was 1 μm, but settabilities of 0.5 μm or less are possible.[4] Since the laser-etched tuner has losses limited by the guiding medium itself and settability an order of magnitude lower than the strip and solder tuners, it is the tuner most suitable for use at millimeter wavelengths. In Fig. 9 the ranges of B / Y_0 for which $P_{tuned} / P_0 > 1$ (see equation (5)) are shown as a function of frequency where the Q of the tuner is given by equation (12) and the settability of the tuner is assumed to be 1 μm. This region represents the region in which the laser-etched tuner is expected to be useful.

Additional improvements in these tuners can be realized by making the substrate thinner or by reducing its dielectric constant. If the dielectric constant is reduced to 2.5, for example, the Q would be increased by a factor of about 3.4, assuming that dielectric loss may be neglected. The value of β would be reduced by a factor of about 1.8, which allows the tuner reactance to be varied in smaller increments.

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References

1. D. J. Ehrlich and J. Y. Tsao, "A review of laser-microchemical processing," *Journal of Vacuum Science Techonlogy*, vol. B1, no. 4, pp. 969-984, October-December 1983.
2. T. F. Finnegan and O. H. Soerensen, "Adjustable microstrip transformer for use with josephson devices in mm-wave ICs," *Electronics Letters*, vol. 17, no. 2, pp. 79-80, 22 January 1981.
3. D. F. Williams and S. E. Schwarz, "Design and performance of coplanar waveguide bandpass filters," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-31, no. 7, pp. 558-566, July 1983.
4. M. Rothschild, J. H. C. Sedlacek, and D. J. Ehrlich, "Photochemical laser etching of Mo and W thin films," *to be published*.
5. S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields And Waves In Communication Electronics*, John Wiley and Sons, New York, 1984.

6. D. F. Williams, "Millimeter-Wave Integrated Circuit Technology," *Phd. Thesis*, University of California, Berkeley, July 1986.

7. D. F. Williams and S. E. Schwarz, "A planar subharmonically-pumped 71 GHz receiver with integral feed antenna," *International Journal of Infrared and Millimeter Waves*, vol. 7, no. 2, February 1986.

8. D. F. Williams and S. E. Schwarz, "Reduction of propagation losses in coplanar waveguide," *Proceedings of the 1984 IEEE International Microwave Symposium*, pp. 453-454, July 1984.

9. K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*, Artech House, Dedham, MA, 1979.

10. M. E. Davis, E. W. Williams, and A. C. Celestini, "Finite-boundary corrections to the coplanar waveguide analysis," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-21, pp. 594-596, September 1973.

11. E. B. Rosa and F. W. Grover, "Formulas and tables for the calculation of mutual and self-inductance," *Uninted States National Bureau of Standards Bulletin*, vol. 8, no. 1, pp. 1-237, January 1912.

12. E. B. Rosa, "The self and mutual inductances of linear conductors," *Uninted States National Bureau of Standards Bulletin*, vol. 4, no. 2, pp. 301-344, January 1907.