MONOLITHIC INTEGRATED CIRCUITS FOR MM-WAVE INSTRUMENTATION

R.A. Marsland*, C.J. Madden, D.W. Van Der Weide, M.S. Shakouri, and D.M. Bloom

Edward L. Ginzton Laboratory, Stanford University, Stanford CA 94305

ABSTRACT

We have fabricated a GaAs sampling head IC which has an estimated bandwidth of 290 GHz. We have also integrated two samplers with a resistive directional bridge to form an S-parameter test-set on a chip. Greater than 10 dB directivity is demonstrated to 60 GHz.

INTRODUCTION

The monolithic nonlinear transmission line (NLTL) has opened up opportunities of speed and performance to electronics once thought the exclusive domain of ultra-fast pulsed lasers [1]. This is accomplished by using the voltage-dependant capacitance of GaAs varactors distributed periodically along a coplanar transmission line to cause shock-wave formation when driven by a large, ~ 10V, signal. We have monolithically integrated a two-diode sampling bridge with a NLTL as the strobe pulse generator (Fig. 1) to achieve a sampling bandwidth of over 290 GHz. We have also integrated two sampling bridges with a resistive directional bridge to form a 60 GHz S-parameter test-set on a chip.

SAMPLING HEAD IC

Previously, we had reported a sampling head IC which measured a 4.0 ps transition time of an attenuated NLTL [2]. To increase the speed of the sampler, improvements were made to the NLTL, the sampling diodes, and layout. Although high-quality mixer diodes and varactor diodes can be fabricated on one chip as shown by Archer *et al.* [3], we chose to place the majority of the NLTL on a separate chip to avoid the necessity of a controlled etch. This chip used a hyperabrupt doping profile as described previously [4] to achieve the maximum compression per unit length. A small NLTL was placed on chip with the sampler since the output of the NLTL chip was limited by the interconnecting bond wires to about 5 ps. The zero bias RC cutoff frequency of the switching diodes was improved from 300 GHz to 1 THz.

Layout is perhaps the most important consideration in designing a high-speed sampler. In this design, the NLTL drives the two ground planes of the RF CPW (Fig. 2). To minimize the inductance of this connection, the ground planes must be close together. However, the sampling diodes must be placed between these ground planes to reduce the inductance of their connection. These conflicting goals are met by imbedding the sampling diodes into the ground planes so that only the portion of the diode which is not at zero RF potential protrudes. To improve yield and provide a better input match, airbridge crossovers were avoided in the RF center conductor and diode connection and instead were used in the ground plane where many could be used in parallel. An interesting simplification of this process has been reported by Yu *et al.* [5] where the airbridge cross-overs in the ground plane were replaced by resistive cross-unders with only minor degradation in performance.

The speed of the sampler was evaluated by using the on-board NLTL test signal generator. With the test NLTL driven at 10 GHz + 100 Hz and the strobe NLTL driven at 5 GHz, the sampled output showed a 160μs 90% to 10% falltime which corresponds to 1.6 ps in real-time (Fig. 2). This is the fastest transition measured to date by an all electronic device. The input-referred noise voltage was $0.6\mu V/\sqrt{Hz}$. The 1dB compression point was -1 dBm. The rise-time of the sampler is estimated from circuit theory to be 1.2 ps [6], which corresponds to a 290 GHz 3-dB bandwidth. However, given the assumptions used by Yu *et al.* [5], the estimated bandwidth of the sampler would be 340 GHz.

THE DIRECTIONAL SAMPLER

To take advantage of the sampler's bandwidth for S-parameter measurements, we have monolithically integrated a resistive directional bridge with two samplers. The bridge has been "unfolded", as shown in Fig. 3, to provide two nodes at zero RF potential across which the strobe pulse may be applied. The bridge is excited from the CPW on the left. Resistors R_3 and R_4 form one side of the bridge and R_1 and the device under test form the other side of the bridge. Diodes D_1 and D_2 are strobed by the voltage applied across the four resistors in series, Vsp. The diodes will conduct heavily on each strobe pulse application until node (b) charges up to $V_b = V_c - V_a + V_{sp}/2$, and node (d) reaches $V_d = V_e - V_a - V_{sp}/2$. Since nodes (c) and (e) have the same RF potential, the voltage at Sampled IF output B is simply $V_B = V_c - V_a$ which is the floating voltage across the bridge. Since it takes many cycles for the diodes to reach a steady-state voltage, the RF and LO frequencies are nearly harmonically related to produce a slowly varying IF output.

The layout of the directional sampler is shown in Fig. 4. As with the sampling head discussed above, there are no airbridge cross-overs in the RF center conductor. On the left side of Fig. 4, airbridges are used to cross over the IF output lead connected to the capacitor bottom plate and to connect the top plate of the capacitor to RF ground. On the right side of Fig. 4, airbridges are again used to cross over the IF lead, but this time the top plate of the MIM capacitor is connected to the two resistors which form half of the directional bridge. The other half of the bridge is formed by the resistor in series with the RF port and the device under test. The strobe signal from a NLTL (not shown in Fig. 4) is applied to the port at the bottom of Fig. 4. and is coupled across the split RF ground through an MIM

* R.A. Marsland is now with New Focus Inc. 340 Pioneer Way, Mountain View, CA 94041.

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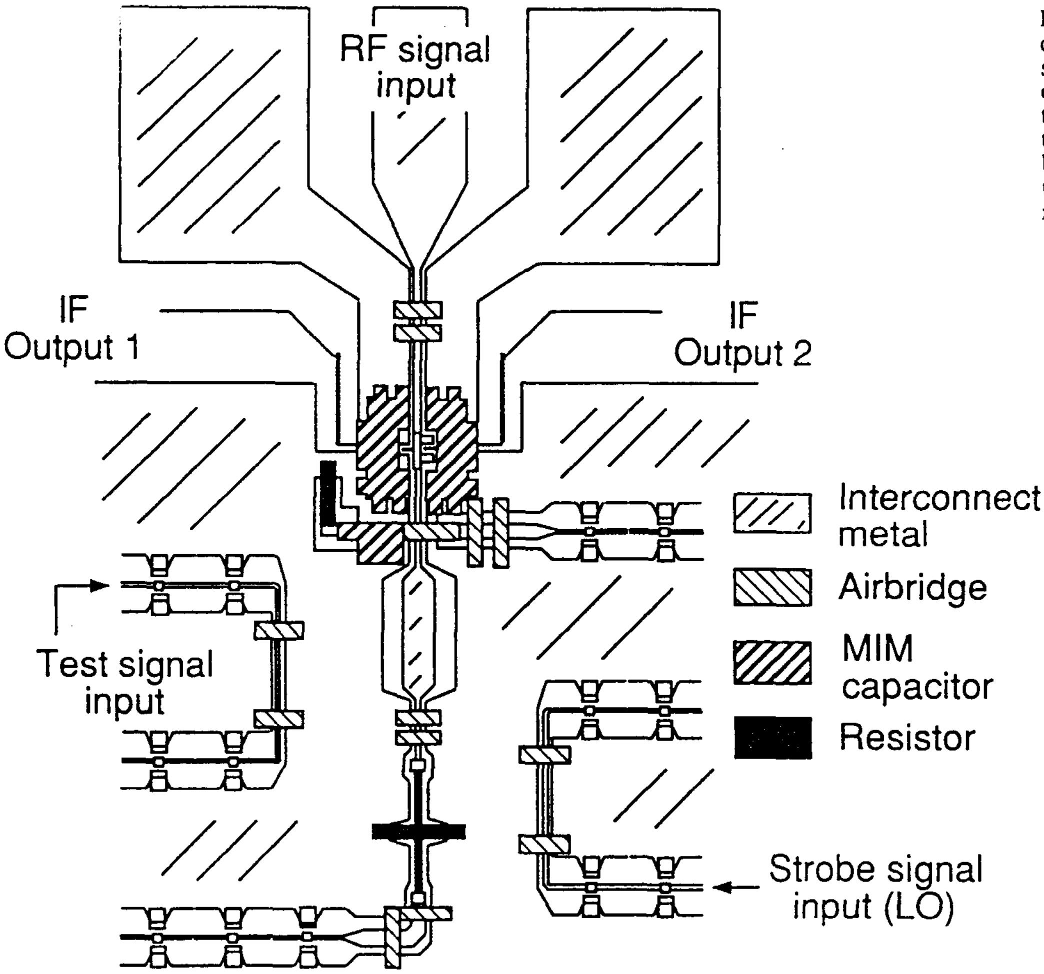


Fig. 1. Plan view of the two diode sampling bridge showing portions of two on-chip NLTLs. The signal to be sampled is input from the top, or a test signal can be used from the NLTL to the left. The NLTL on the right provides the strobe.

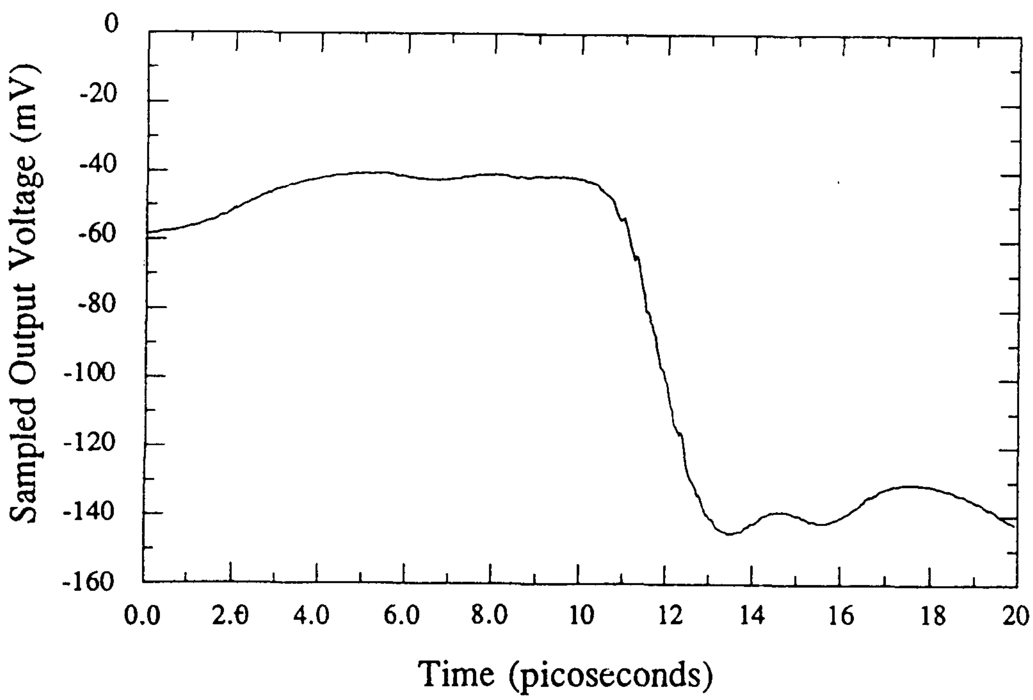


Fig. 2. 1.6 ps falltime output of a 10:1 attenuated NLTL measured by the diode sampling bridge. Noise on the edge is due to timing jitter.

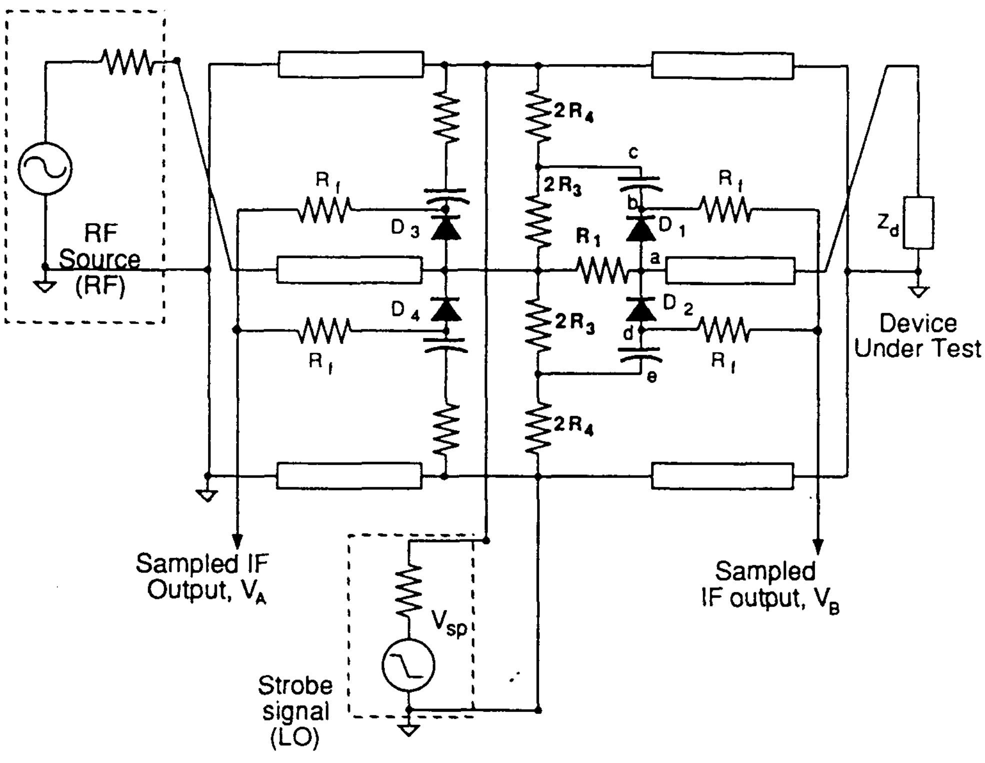


Fig. 3. "Unfolded" directional bridge with two samplers. The sampling diodes on the left sample the voltage applied to the bridge while those on the right of the figure sample the floating voltage across the bridge.

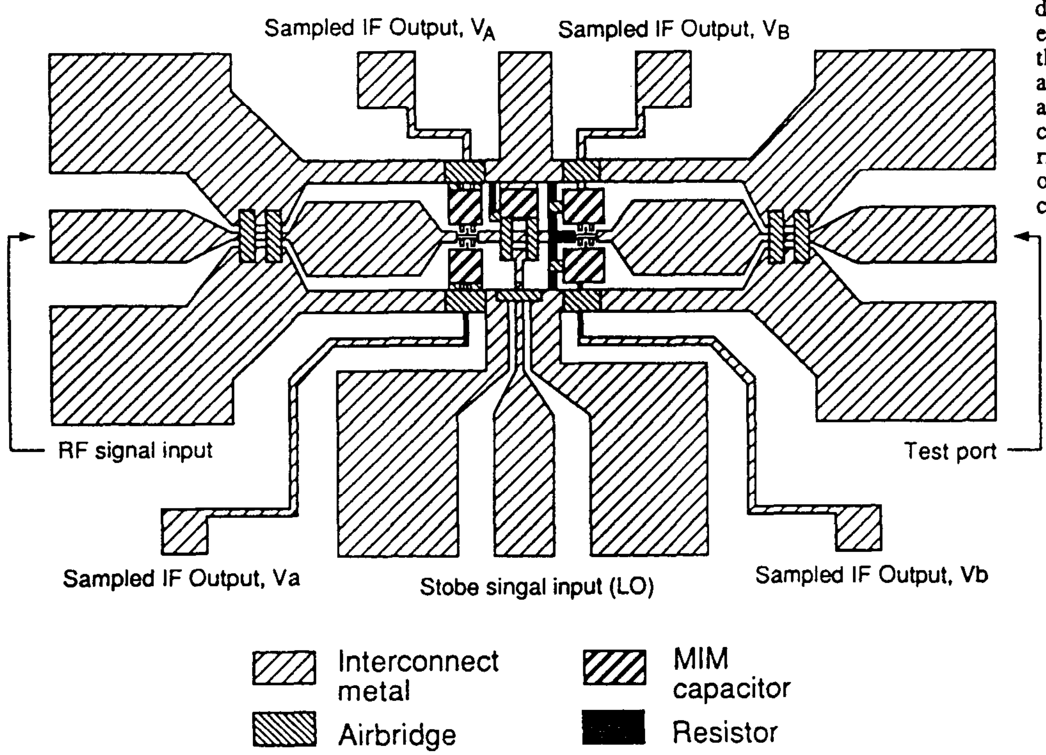
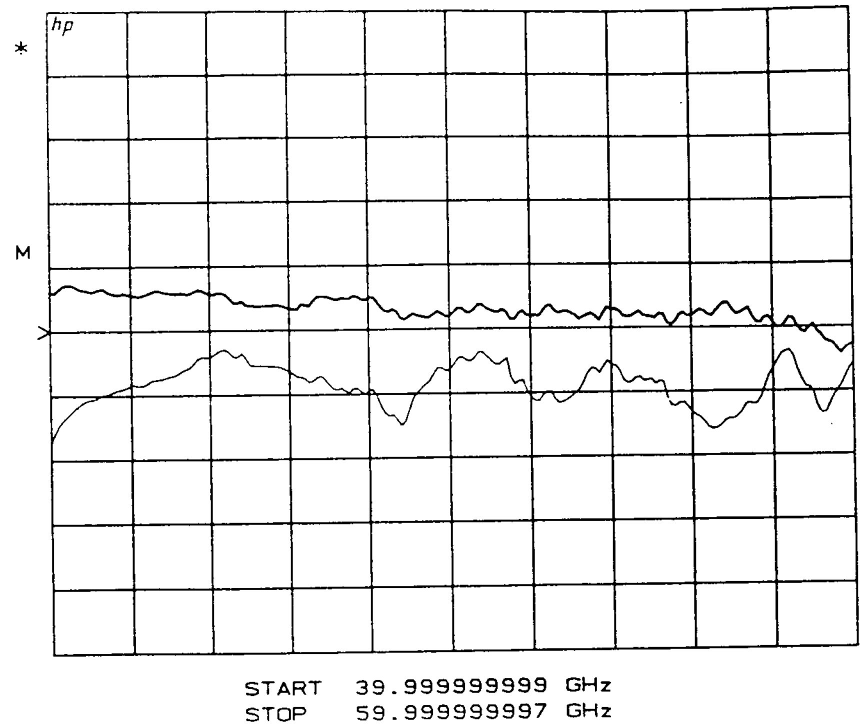


Fig. 4. Plan view of the directional bridge. RF excitation is applied from the left, the LO strobe is applied to the bottom port, and the device under test is connected to the port on the right. Each sampler has two outputs which are ac-coupled together off-chip.

Fig. 5. 40 to 60 GHz uncalibrated S_{11} of an open 2.4 mm connector (heavy trace) and that of a 2.4 mm load (lighter trace). S_{11} of the open decreases with frequency due to radiation. Vertical scale is 10 dB/ division.



coupling capacitor and a parallel LO -terminating resistor. The strobe signal propagates along the split RF ground until it reaches the airbridges shorting the two grounds together approximately 200 µm from the sampling diodes on either side. The strobe signal, reflected from the airbridge short, returns to terminate the sampling interval after approximately 5 ps.

Ideally, the ratio of the vector voltages at the intermediate-frequency (IF) output is directly proportional to the reflection coefficient S_{11} for impedances near 50Ω, but calibration is required to extract S_{11} for loads with large reflection. This is because several resistors of the conventional directional bridge have been omitted for convenience in layout.

After packaging with a NLTL strobe pulse generator, the directivity of the "directional sampler" was measured from 3 to 60 GHz and found to be typically 10 dB. Fig. 5 shows the directivity measurement for the 40 to 60 GHz band. This is comparable with available coaxial directional couplers but in monolithic form with potential for much higher frequency operation. The relatively low directivity is due to the wide variation in the value of the N^+ resistors (± 22%). The theoretical directivity of this bridge based on DC measurement of the resistors is 12 dB. This can be readily improved by fabricating resistors with better tolerance. 23 dB directivity is expected for resistors with an absolute tolerance of ±10% but well matched to each other.

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