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A PLANAR SUBHARMONICALLY-PUMPED 71 GHz RECEIVER WITH INTEGRAL FEED ANTENNA

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Key words: millimeter-wave receiver, millimeter-wave integrated circuit, coplanar waveguide.

Introduction

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Introduction

At millimeter wavelengths many distributed circuits take on dimensions compatible with photolithography. The small size of millimeter-wave components allows complex circuits to be realized on single substrates, eliminating the need for expensive, bulky waveguide components. Considerable work on planar circuits in the 70-110 GHz region has been reported.

Kerr, et al [1], Clifton, et al [2], and Zah, et al [3] have described integrated receivers with low-gain feed antennas meant for coupling to lenses or horns. These receivers are of the simplest design and require an external quasi-optical diplexing apparatus. Simple receivers can be used to advantage in imaging applications. There some reduction in the efficiency of the individual receivers can be accepted, since the overall rate of information acquisition increases in proportion to the number of receivers in the array. A single external quasi-optical diplexer can perform the diplexing for an entire array of receivers, as has been demonstrated by Zah, et al [3]. However, external quasi-optical diplexers are less attractive for applications in which only one lightweight, low cost receiver is required.

Recently Bauhahn, et al [4] and Yuan, et al [5] have described more sophisticated integrated mixers with excellent preformance. Because these mixers have internal planar diplexers they are better suited to applications where a single lightweight receiver with high performance is required. To our knowledge, the mixer reported by Yuan, et al [5] has the lowest conversion loss of any planar mixer yet reported in this frequency range. These authors reported a 4.6 dB conversion loss over a narrow band (corresponding to low i.f. frequencies) centered at 91.1 GHz. Their broad band conversion loss over the range 73.6 GHz to 83.6 GHz was reported to be in the range of 5 to 9 dB. It should be possible to integrate planar antennas with these mixers, but it may be somewhat difficult to integrate microstrip with a suitable antenna. In order to be suitable as a feed, such an antenna must provide a reasonably symmetric pattern, together with adequate efficiency and a minimum gain on the order of ten dB. A large bandwidth is also desirable. The characteristics of the mixers mentioned above are compared in Table I.

In this paper we report on a broad-band millimeter-wave integrated-circuit receiver at 71 GHz. To the authors' knowledge, the present receiver represents the highest level of integration yet reported for a planar receiver in the 70-110 GHz frequency range. It incorporates a high gain, high efficiency planar antenna and an integrated planar diplexer based on CPW filters [6]. Unlike the receivers and mixers mentioned above, it is subharmonically pumped. This is advantageous at millimeter wavelengths, where local oscillator performance deteriorates as frequency increases. The broad band conversion loss of 6.5 dB reported here is comparable with the broad band conversion loss of 5-9 dB reported by Yuan, et al [5]. Coplanar waveguide (CPW) is used in place of microstrip. A unique plated-post technology is used to mount the beam-lead diodes and to eliminate wire bonds. The use of coplanar waveguide (with its larger substrate thickness) and the plated-post technology should allow the circuit to be scaled to higher frequencies more easily than is possible with other planar technologies [6,7] while remaining compatible with conventional beam-lead devices.

Mixer Operation

A diagram of the mixing circuit is shown in Fig. 1. Filters provide access to each frequency of interest through physically isolated ports, and select the subharmonic mixing product $\omega_{\mathrm{if}}=\omega_{sig}-2\omega_{lo}$. An anti-parallel diode pair suppresses fundamental mixing of the local oscillator (at 32 GHz) with the signal (66-76 GHz). The product of the signal and the second harmonic of the local oscillator appears at the intermediate frequency (if) port. The anti-parallel diode pair also has the advantage of suppressing down-converted local oscillator noise. Image enhancement, (the internal reactive termination of the image frequency $\omega_{image}=2\omega_{lo}-\omega_{\mathrm{if}}$,) and suppression of local oscillator power radiated by the antenna are also more easily achieved in the subharmonic receiver than in a fundamental mixer. This is because the local oscillator frequency is widely separated form the image and signal frequencies, easing filter requirements.

Planar Antenna

The antenna is composed of an array of slots coupled by one-wavelength sections of CPW, as shown in Fig. 2. It is similar to designs by Nesic [8], but has two arrays of radiating slots

	Ref.	Date	f_o (GHz)	L_{mixer} (dB)	T_m (K^o)	f_{co} (GHz)
This work	---	1985	71	6.5	900	600
Kerr	[1]	1977	112	8.6	1000	3000
Clifton	[2]	1981	110	6.8	680	5000
Zah*	[3]	1985	94	8.0	---	1100
Bauhahn	[4]	1984	94.5	---	1060	1000
Yuan	[5]	1985	91.1	4.6	---	600

Table I. Comparison of planar mixers and receivers in the 70-110 GHz range reported in the literature. Listed are the RF center frequency f_o, the mixer conversion loss L_{mixer}, the mixer single sideband noise temperature T_m, and the cutoff frequency of the diodes used f_{co}.

coupled to CPW feeds, which results in comparable E and H plane beam-widths of 32 and 45 degrees respectively. The estimated gain at 71 GHz is 12 dB. (The design value of the gain, based on low-frequency simulation, is 13.5 dB; the difference is due to resistive loss.) The slots radiate primarily downward through the substrate because of its high dielectric constant. A shorting plane above the antenna is used to suppress a small amount of radiation directed upward into the air.

*Zah, et al [3] did not calculate L_{mixer} explicitly. In order to compare results on a uniform basis, we estimated this value from their data by subtracting coupling losses from overall measured loss.

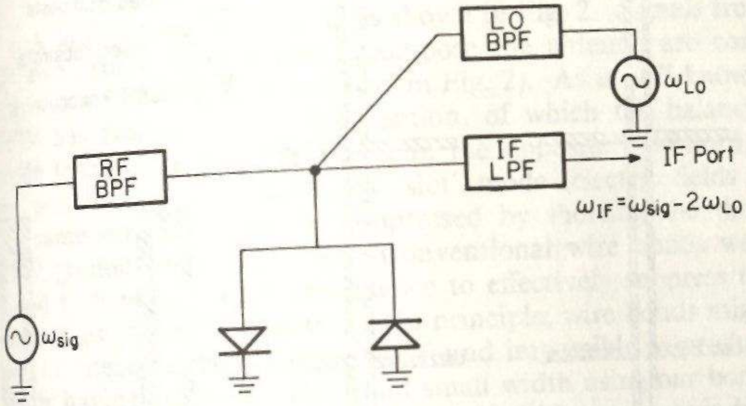

Fig. 1. Schematic diagram of the subharmonic mixer.

The side lobe levels of planar antennas are difficult to control, and as the gain of the antenna increases the ratio of the power lost into the sidelobes to the total radiated power can become very large. While the side lobe levels of low gain (< 5 dB gain) planar antennas are easily made low enough to prevent a significant amount of power being radiated outside of the main lobe, the same is not true of planar antennas with higher gain. For example, our measurements on vivaldi antennas with gain similar to the gain of the antenna reported here indicate that only 25% or less of the radiated power is in the main lobe. Simulation measurements performed on the antenna used in this receiver indicate that 65% of its radiated power is in the main lobe. Thus, with a deduced gain of 12 dB, this antenna radiates a an unusually high percentage of its total radiated power (65% of its radiated power and 46% of the input power, the difference being due to ohmic losses) into its main lobe.

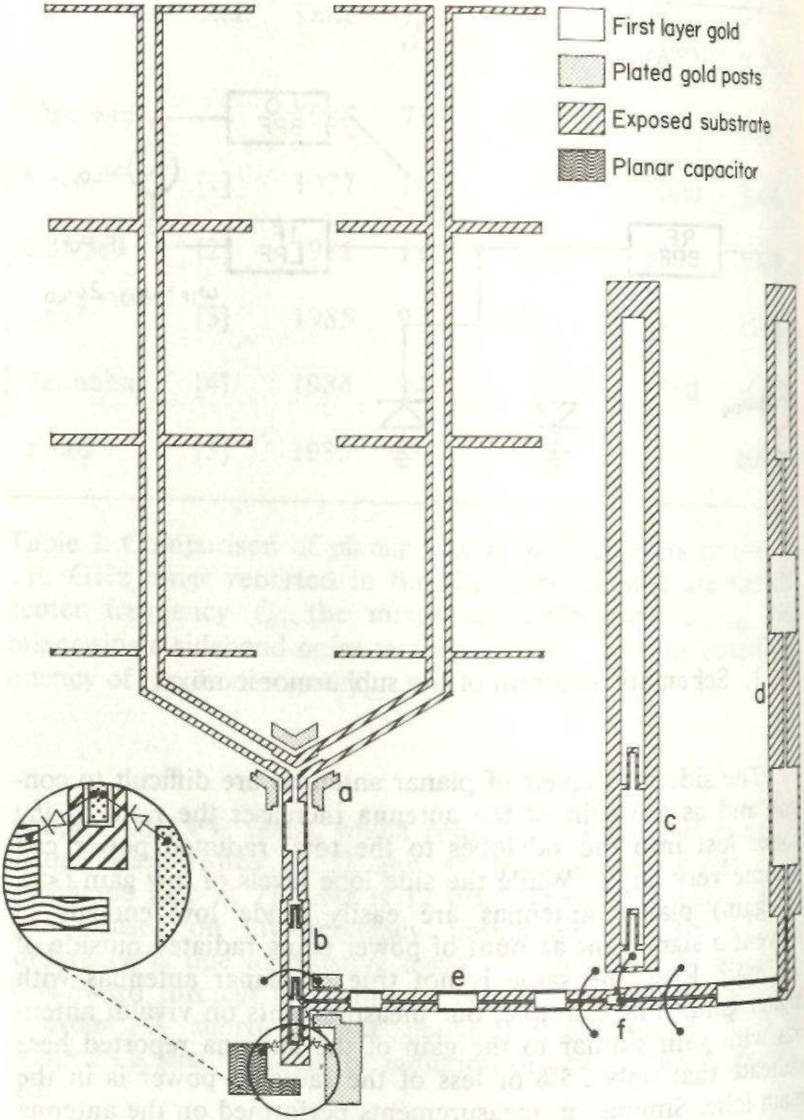

Fig. 2. Millimeter wave receiver (top view). a) CPW "T" junction combines the signals from each array of slots. The cover plate is not shown. b) RF band-pass filter (66-76 GHz). c) LO band-pass filter (32 GHz). d) IF low-pass filter (0-18 GHz). e) LO-IF low-pass filter (0-36 GHz). This filter presents an open circuit to the diode pair at the RF frequencies. f) Low frequency "T" junction.

Mixer Circuit

A top view of the receiver is shown in Fig. 2. Signals from the two arrays of slots which compose the antenna are combined in a CPW "T" junction ("a" in Fig. 2). As is well known, CPW has two modes of propagation, of which the balanced mode (electric fields in each slot in the opposite direction) is the one desired. The undesired "slot" mode (electric fields in the same direction) can be suppressed by shorting the three CPW ground planes together. Conventional wire bonds were found to have too much inductance to effectively suppress the slot modes at the "T" junction. (In principle, wire bonds might well be adequate. However, it was found impossible to produce bonds having both low height and small width using our bonding facilities.) In order to obtain a short with very low inductance, a gold post is plated on each of the three ground planes. The posts are first defined photolithographically and then plated to a height of 17um. A gold top plate (not shown) is then thermo-compression bonded between the three gold posts, providing a low-inductance short between the ground planes. The height of the posts can be controlled accurately during the plating process, allowing the excess capacitance introduced by the top plate to be compensated for by a reduction of the width of the center conductor of the CPW. This technique is scalable to frequencies of several hundred GHz because both the vertical and lateral dimensions of the posts can be precisely defined.

The two band-pass filters of Fig. 1 are realized as gap-coupled resonant sections ("b" and "c" in Fig. 2) [6]. The two low-pass filters ("d" and "e" in Fig. 2 with stop bands around 32 and 71 GHz respectively) are realized by cascading alternating high and low impedance sections of CPW. The section lengths are approximately a quarter-wavelength long at the filter stop band frequency. The section lengths and impedances were computer-optimized to give the best performance. Bond wires are adequate for even-mode suppression at the low-frequency junction "f", because only the local oscillator and IF frequencies are present at that point. A plated-post "T" junction might also be used at "f" if the circuit were scaled to higher frequencies.

GaAs beam-lead diodes were employed as the non-linear mixing elements. They were bonded to gold-plated posts similar to those employed in the "T" junction described above, as shown in Fig. 3. In the usual mounting method the beam-lead diodes are bonded directly to the conductors of a CPW section. The spacing of the guide conductors must be as large as the beam-lead structure itself, in order to avoid excessive capacitance or actual contact between the diodes and the CPW. However, experiments on scale models show that the energy radiated by the diode mounting structure is reduced when the spacing between the CPW conductors is reduced. Since the size of the beam-lead diodes is fixed by mechanical considerations, a considerable amount of power can be radiated away by a conventional mounting structure. In the present design the CPW section over which the beam-lead diodes are suspended is no longer constrained to be as wide as the beam-lead structure itself. The diodes can now be mounted directly above a narrowly-spaced CPW section without creating excessive capacitance or short circuits to the ground planes, thus reducing the energy radiated by the diode mounting structure. This mixer mount is scalable upwards in frequency even though the dimensions of the beam-lead diodes remain fixed. Bypass capacitors are integrated into the mounting structure (see Fig. 3) allowing the d.c. bias of the two diodes to be adjusted individually. This provides a degree of compensation for differences between the two diodes. Experimentally, a 1 dB improvement in conversion loss is obtained by biasing the diodes separately. The receiver was fabricated by ion milling 1 um thick gold conductors on a 200um thick sapphire substrate. It is designed for a 10 GHz instantaneous bandwidth centered at 71 GHz and a local oscillator frequency of 32.2 GHz. The GaAs beam-lead diodes were supplied by the Hughes Aircraft Company's Electron Dynamics Division and had a cutoff frequency of 600 GHz.

Measurements

Stephan, et al [9] have characterized planar receivers by their isotropic conversion loss, which is the most easily measured figure of merit of a planar receiver. The isotropic

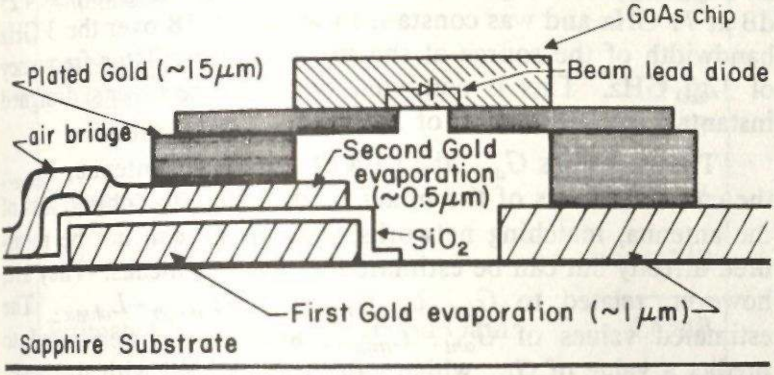

Fig. 3. Diode mounting structure. The GaAs Beam-lead diode is suspended above the substrate on plated gold posts. Note that the d.c. bias capacitor is integrated into the mounting structure and that the width of the gap at the surface of the substrate is not constrained to be as large as the beam-lead diode.

conversion gain (reciprocal of isotropic conversion loss) is defined by $G_{iso}=P_{\mathrm{if}}/P_{iso}$ where P_{if} is the intermediate frequency output power of the receiver when illuminated by a source and P_{iso} is the power which would be received by an ideal isotropic antenna when illuminated by the same source. P_{iso} is measured by placing a standard gain horn (TRG E861 Standard Gain Horn) with gain G_{sgh} at the receiver's position while it is illuminated by the same source. P_{iso} is then given by $P_{iso}=P_{sgh}/G_{sgh}$, where P_{sgh} is the power received by the standard-gain horn, as measured by a calibrated power meter (Hewlett Packard 431B Power Meter with a Hughes 44895H calibrated head). P_{if} was measured at the intermediate frequency of 6.5 GHz with a spectrum analyzer (Tektronix 492

Spectrum Analyzer calibrated against a Hewlett Packard 435B Power Meter with a Hewlett Packard 8481A calibrated head) when the receiver was illuminated by a source at 71 GHz. The isotropic conversion gain of the receiver was found to be +4.25 dB at 71 GHz and was constant to within .5 dB over the 3 GHz bandwidth of the source at the fixed local oscillator frequency of 32.2 GHz. This is consistent with the receiver's designed instantaneous band width of 10 GHz.

The quantities G_{ant}, the gain of the planar antenna, L_{mixer}, the conversion loss of the mixer, and L_{ohmic}, the ohmic loss of the antenna, matching networks, and filters, can not be measured directly but can be estimated by various means. They are, however, related to G_{iso} by $G_{iso} = G_{ant} - L_{mixer} - L_{ohmic}$. The estimated values of G_{ant}, L_{mixer}, and L_{ohmic} were used to predict a value of G_{iso} which can be compared with the measured value. An estimate of the ohmic loss was derived from resistivity measurements of our evaporated gold films, with skin effect taken into consideration. The filter radiation losses and the antenna gain are known from scale model measurements. The mixer conversion loss was calculated by a modified version of a computer program given to us by Dr. A.R. Kerr and Dr. P.H. Siegel, described in [10]. The embedding impedances and the diode parameters required by the computer program were determined from scale model measurements and d.c. measurements performed at Hughes Aircraft Company, respectively. The resulting values of these quantities are summarized in Table II. The value of G_{iso} predicted from the estimates in Table II (4.65 dB) is in good agreement with the experimentally observed value of 4.25 dB. Thus while it is not possible to verify experimentally with absolute certainty any of the estimates in Table II, there is good reason to believe that they are reasonably accurate.

The computer program used to calculate mixer conversion loss was also used to calculate the mixer single side band noise temperature T_m of 900 degrees Kelvin. While this value of noise temperature was not confirmed experimentally, we believe it to be reasonably close to the actual value given our confidence in the calculated mixer conversion loss. The measured single side band noise temperatures and conversion losses

Antenna directivity (1 GHz scale model)	+13.5 dB
Antenna ohmic loss	- 1.5 dB
Antenna Gain	12.0 dB
RF bandpass filter loss	
Ohmic loss	- .2 dB
Radiation loss	- .2 dB
Mixer conversion loss	- 6.5 dB
IF low-pass filter loss	- .45dB
Estimated Isotropic Conversion Gain	+ 4.65dB
Measured Isotropic Conversion Gain	+ 4.25dB

Table II. Receiver performance estimates. The signal, local oscillator, and intermediate frequencies are 70.95 GHz, 32.2 GHz, and 6.55 GHz respectively.

of other mixers in this frequency range are listed in Table I for purposes of comparison.

Conclusion

The receiver described above is highly planar and is integrated to a high degree, incorporating mixer, feed antenna, and diplexer. It combines high performance with small size, light weight, and simple fabrication. It is believed that the design is scalable to frequencies of several hundred GHz, the main performance limitations being related to the cutoff frequency of the beam-lead diodes and the increasing ohmic loss of the CPW. The overall measured isotropic conversion gain of 4.25 dB compares well with the expected value of 4.65 dB. The planar antenna provides a pattern that is reasonably well-suited for use as a feed, having good gain, pattern, and efficiency.

With a deduced gain of 12 dB, it radiates a high percentage of its power (65% of its radiated power and 46% of the input power) into its main lobe. The deduced broad band conversion loss of the receiver reported here is comparable to that of Yuan et al [5]. Thus the high level of integration exhibited here is not accompanied by a loss of performance.

In [11] is is shown that it is possible to reduce the loss of CPW by a factor of four by employing grooved substrates. It should be feasible to make use of this technique to reduce the receiver's ohmic loss. It may also be possible to provide adjustable reactive compensation for the diode capacitance. Calculations indicate that if the loss reduction scheme of [11] were employed and if the diode capacitance were tuned, an overall isotropic conversion gain of +7.825 dB would be achieved with this design. In that case the overall ohmic loss would be .675 dB, and the broad band SSB conversion loss would be 5.0 dB.

Acknowledgements

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