Quasi-Optical Integrated Antenna and Receiver Front End

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Abstract —A quasi-optical receiver front end applicable to both microwave and millimeter-wave receiver arrays is presented. Two planar MIC quasi-optical receiver circuit designs that integrate a coupled slot antenna, a Schottky diode balanced mixer, and a local oscillator on the same substrate are described. The even-mode/odd-mode characteristics of the coupled slotlines are used to achieve intrinsic RF/LO and RF/IF isolation. To demonstrate circuit feasibility, X-band scaled models of the circuit using a Gunn diode oscillator on an Epsilam-10 substrate, and a MESFET local oscillator on a R/T duroid substrate were built and tested. Results of these tests are included.

I. Introduction

IN MANY MILLIMETER-WAVE applications such as quasi-optical receiver arrays, it is essential to use planar integrated circuit technology to reduce the size and cost of the system. When one uses conventional discrete receiver front end components to build a receiver array, the system becomes impractical due to its complexity and cost. With the advance of MMIC technology, researchers have demonstrated MMIC mixers [1] and planar quasi-optical mixers [2]–[4] that combine the functions of antenna and conventional mixer. These mixers reduce the size and complexity of the circuit considerably. They have potential applications in receiver arrays and other large systems. However, these mixers use external local oscillator (LO) circuits. Problems arise when one tries to feed LO power to an array of such units. In [2], the local oscillator is fed by a waveguide. In [3] and [4], the LO signal is coupled through free space using a waveguide horn to irradiate LO power to the mixers. This technique, although simple, involves substantial loss of LO power. Recently, a monolithically integrated Gunn oscillator operating in the millimeter-wave frequency range was reported [5]. This oscillator uses a coplanar waveguide resonator to form its planar structure. The research effort in [5] opens the door for a monolithically integrated quasi-optical receiver that uses a built-in Gunn local oscillator feeding the mixer.

In the present work, the concept of integrating the coupled slot antenna, the Schottky diode balanced mixer, and the LO oscillator on the same substrate is introduced. The even mode of the coupled slotline (CSL) is used for receiving the RF signal, and the odd modes of the CSL is used for guiding the LO and IF signals. Since the even and odd mode of the CSL are orthogonal, RF/LO and RF/IF isolations are achieved.

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Two such quasi-optical receiver circuits, one using a Gunn oscillator, the other using a MESFET oscillator, are described. Diagrams of the circuits are shown in Figs. 1 and 2. To demonstrate the feasibility of the designs, X-band models of the receivers were built on Epsilam-10 substrate and R/T duroid substrates. The RF–IF conversion characteristics and the receiving patterns of the circuits were measured.

The basic building block of the receivers is a half-wave coupled slot antenna. Before giving a detailed description of the receiver circuit, the properties of the coupled slotlines and coupled slot antenna will be introduced.

II. Coupled Slotlines and Coupled Slot Antenna

It is generally known that coupled slotline supports two orthogonal modes: the even and odd modes. Fig. 3 shows the field distributions of the CSL even and odd modes. The CSL excited by the odd mode becomes a coplanar waveguide (CPW), which is less susceptible to radiation at discontinuities than the even mode. As will be discussed in the next section, the odd mode of the CSL will be used to propagate the LO signal. The even-mode characteristics of the CSL resemble those of a pair of single slotlines with coupling effect between them. When a CSL of approximately half a wavelength is short-circuit terminated at both ends and is excited by the even-mode RF signal, it becomes a pair of resonant slot antennas (see Fig. 4). The coupling of the two slots decreases as the spacing between them increases. The CSL even- and odd-mode propagation constants and impedances can be calculated using numerical techniques such as the spectral-domain method [6], [7].

The coupled slot antenna of Fig. 4 is not suitable for use in quasi-optical antenna mixers. If mixer diodes are placed in the slots to form a balanced mixer, the ends of the slots (which are short-circuited) are too close to the diodes compared with the IF signal wavelength, and little IF power can be picked up.

In the present work, the coupled slot antenna is modified as shown in Fig. 5. The ends of the connected coupled slot (Fig. 5) are virtual short circuits for the

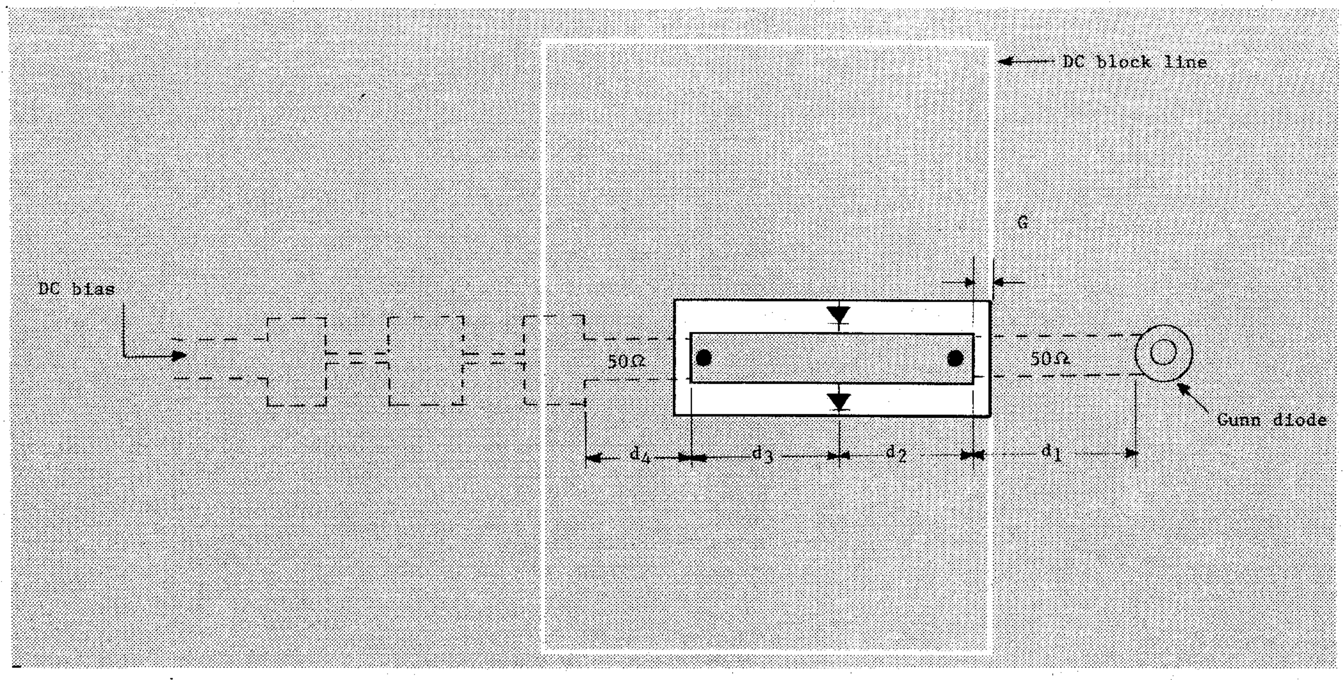

Fig. 1. Receiver circuit using the Gunn diode oscillator.

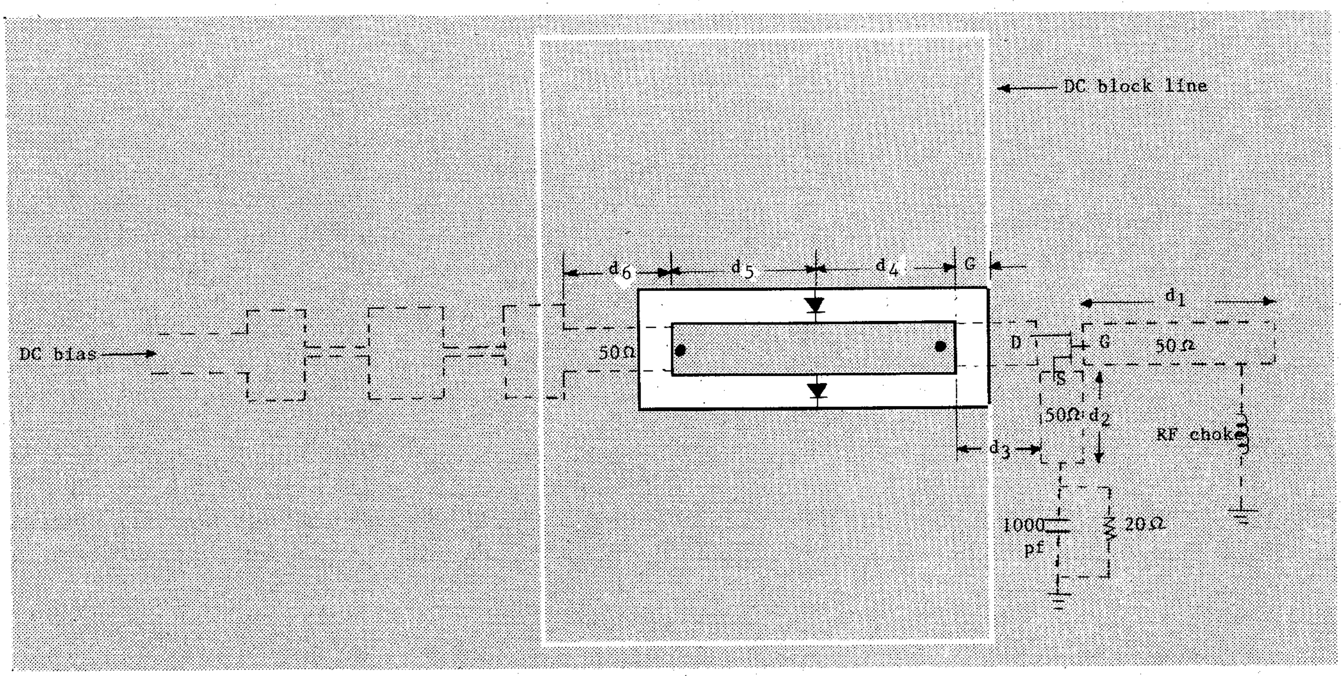

Fig. 2. Receiver circuit using the MESFET oscillator.

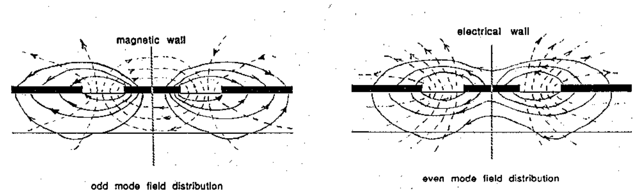

Fig. 3. Even mode and odd mode of the coupled slotline.——— electric field lines; --- magnetic field lines.

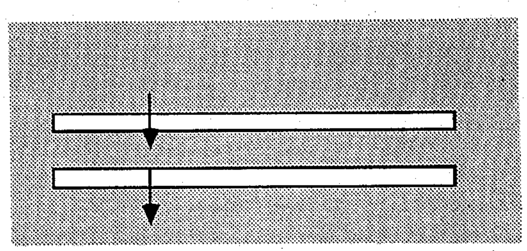

Fig. 4. Pair of slot antennas.

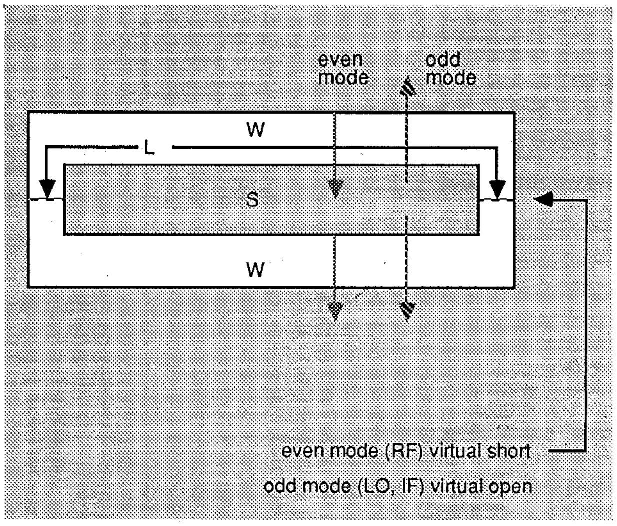

Fig. 5. Connected coupled slot antenna.

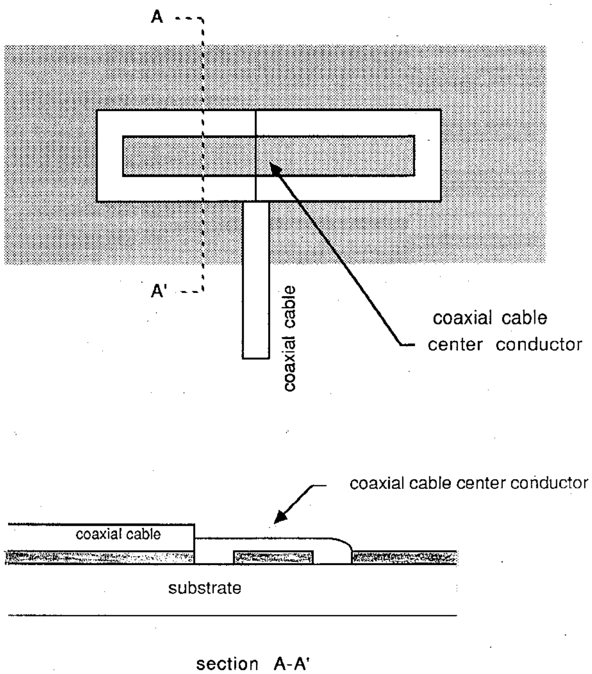

Fig. 6. Coaxial cable fed coupled slot antenna for measuring the RF receiving patterns.

even-mode RF signal. By making the antenna length L (Fig. 5) half a wavelength at the even-mode RF signal, the connected coupled slot resembles the half-wave resonant antennas of Fig. 4. For the odd-mode LO and IF signal, the ends of the connected coupled slot (Fig. 5) are virtual open circuits. This dual characteristic is used in the quasi-optical receiver design to provide intrinsic RF–LO and RF–IF isolation.

Knowing the even-mode propagation constant and the length L, the resonant frequency of the half-wave resonant antenna can be estimated. When designing the coupled slot antenna, the spacing S between the two slots should be kept reasonably small so that the two slots receive the RF signal at approximately the same phase. The slot width W also needs to be small to eliminate higher order modes. A 10-GHz coupled slot antenna was built on an Epsilam-10 substrate of thickness 0.635 mm, as shown in Fig. 6. This antenna was fed by a coaxial cable that was placed a short distance from the center of the slots for better impedance matching [8]. The antenna gains at the resonant frequency was measured to be 4 ± 1 dB. These antenna gains were obtained by comparing the RF received by the CSL antenna with the power received by a standard gain horn. The receiving patterns of this coaxial-cable-fed antenna were experimentally determined. The results are shown as dotted lines in Figs. 12 and 13 along with the IF patterns of the complete receiver circuit (the one uses the Gunn oscillator). The antenna patterns resemble that of a single-slot resonant antenna if the spacing of the two slots is small and the two slots see RF signal of the same phase.

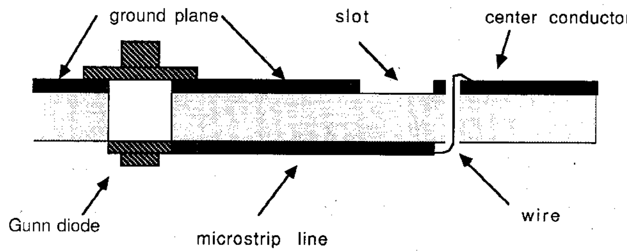

Fig. 7. Cross-sectional view of the Gunn diode connection.

III. Overview of the Receiver Circuits

The basic building block of both circuits (Figs. 1 and 2) is the connected coupled slot (Fig. 5), which is used simultaneously as an antenna (using the even mode) and in constructing the local oscillator resonator (using the odd mode). From the polarizations of the RF and LO signals (see Fig. 5), it can be seen that a balanced mixer is formed by placing a pair of Schottky diodes inside the slots with the polarity shown in Figs. 1 and 2. To avoid biasing the Schottky diodes by the local oscillator dc bias voltage, an extremely thin gap encircling the region containing the coupled slot is made on the ground plane. As discussed earlier, the ends of the connected CSL are virtual shorts for the even-mode RF signal and are virtual opens for the odd-mode LO and IF signals. Therefore, the RF signal is intrinsically isolated from LO and IF port.

In the diode local Gunn oscillator, the diode is placed at one end of the coupled slot as shown in Figs. 1 and 7. The resonator circuit consists of the microstrip line, the coupled slot, the Schottky diodes, and the IF microstrip low-pass filter. The low-pass filter and the microstrip line are fabricated on the back side of the substrate. These components are connected to the center conductor of the CSL by wires through the substrate. The ground plane facilitates heat sinking of the Gunn diode.

In the MESFET local oscillator design, the Gunn diode is replaced by the MESFET and its embedding microstrip line circuit. The drain output circuit of the MESFET oscillator consists of the coupled slot, the mixer diodes, and the IF low-pass filter.

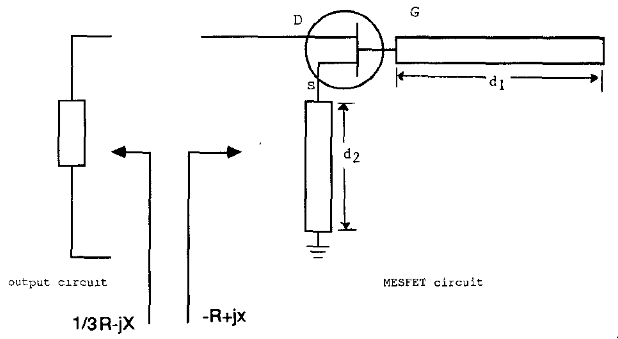

Fig. 8. MESFET circuit.

TABLE I
DIMENSIONS OF THE CIRCUIT OF FIG. 1

dielectric constant	10.2
substrate thickness	0.635 mm
slot width (w)	1 mm
slot spacing	1 mm
G	0.5 mm
d_1	1.9 mm
d_2	3.5 mm
d_3	4.0 mm
d_4	3.1 mm

TABLE II
DIMENSIONS OF THE CIRCUIT OF FIG. 2

dielectric constant	2.5
substrate thickness	0.79 mm
slot width (w)	1 mm
slot spacing	2 mm
G	1 mm
d_1	12 mm
d_2	4 mm
d_3	6.5 mm
d_4	6 mm
d_5	6.5 mm
d_6	12 mm

IV. CIRCUIT DESIGN PRINCIPLES

The dimensions of the connected coupled slot are first determined based on the considerations stated in Section II. Then, the optimum position of the Schottky diodes needs to be found. The optimum position is where the coupled slot antenna input impedance best matches the Schottky diodes' impedance with the diodes at operating LO power. This position was found experimentally to be a small distance away from the center of the coupled slots.

For the Gunn diode local oscillator, the impedance of the Gunn diode, $-R+jx$, at the desirable LO drive power level, bias condition, and LO frequency is first measured using the load-pull method. Next, the resonant circuit of the local oscillator needs to be designed so that the Gunn diode sees an embedding circuit impedance of $R-jx$ at the LO frequency. To design the resonant circuit, we first note that the low-pass filter presents a short circuit to the LO signal. The impedance of the Schottky diode at the LO frequency under the LO driving condition can be found by either large-signal measurement or large-signal computer simulation. Since the position of the Schottky diodes was determined previously, values of d_2 and d_3 in Fig. 1 are fixed. The resonator circuit designer simply uses a Smith chart to find values of d_1 and d_4 so that the resonant circuit has an impedance of $R-jX$.

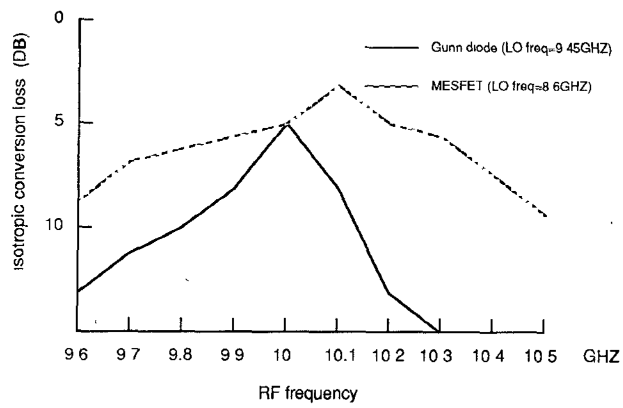

Fig. 9 Isotropic conversion loss versus RF frequency.

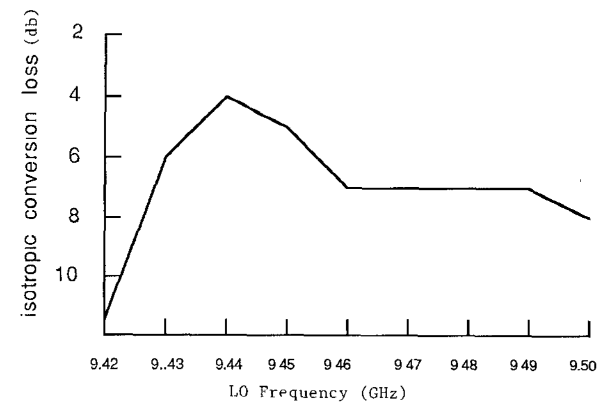

Fig. 10. Isotropic conversion loss versus LO frequency (Gunn diode, RF freq. = 10.0 GHz).

For the circuit of Fig. 2, the MESFET circuit of Fig. 8 is first designed. The microstrip line lengths d_1 and d_2 are determined from the MESFET small-signal S parameters, so that the negative impedance seen from the drain port has the largest value. The output circuit design follows the same principles as in the Gunn oscillator design. However, since the small-signal S parameters were used, R_{out} was chosen to be 1/3 of R_{in} (see Fig. 8). This design provided an output power level sufficient for LO drive.

The dimensions of the circuits of Figs. 1 and 2 are listed in Tables I and II.

V. CIRCUIT PERFORMANCES

The circuit using the Gunn oscillator is fabricated on an Epsilam-10 substrate of thickness 0.635 mm, and the circuit using the MESFET is fabricated on an R/T duroid substrate of thickness 0.79 mm. Since the circuit combines the functions of antenna and mixer, the conventional definitions of antenna gain and mixer conversion loss cannot be used to determine circuit performances. To characterize the efficiency of the receiver as one device, isotropic conversion loss L_{iso} is used [3]. L_{iso} is defined as

$$L_{iso} = 10 * \log(P_{IF}/P_{iso})\ \mathrm{dB} \quad (1)$$

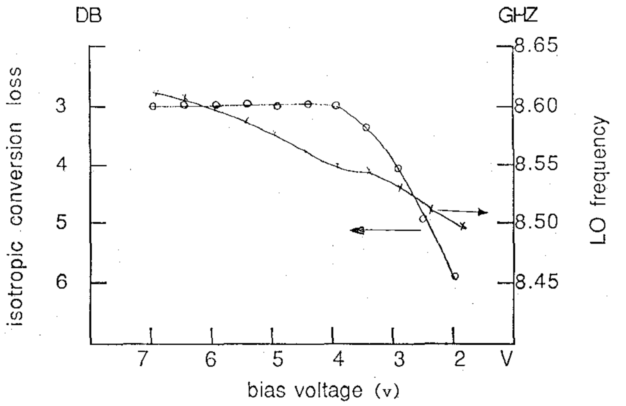

Fig. 11. Isotropic conversion loss and LO frequency versus bias voltage (MESFET oscillator, RF freq. = 10.1 GHz).

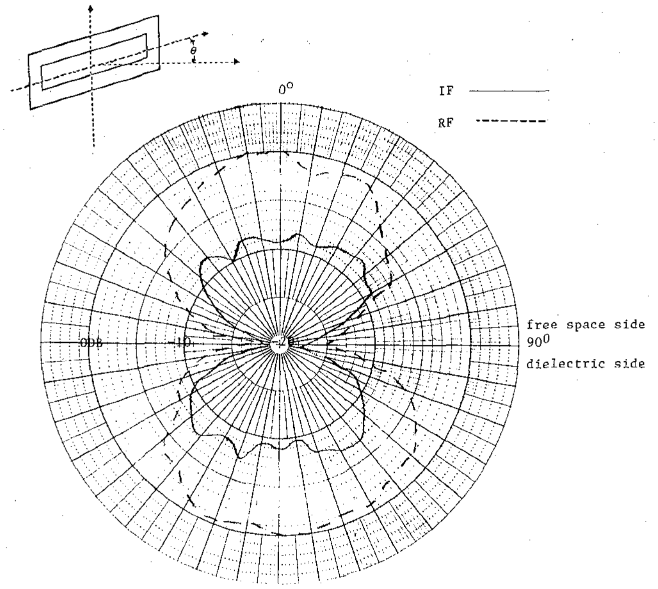

Fig. 12. Relative plots of IF power versus azimuthal angle q and the coupled slot antenna RF H-plane pattern.

where P_{IF} is the down-converted IF power obtained. P_{iso} is the RF power that would be received if the receiver circuit were replaced by a fictitious isotropic antenna under the same measurement conditions. L_{iso} versus RF frequency is shown in Fig. 9. L_{iso} versus LO frequency is shown in Figs. 10 and 11. Here, the LO frequency is changed by adjusting the bias voltage. Figs. 12 and 13 show the plots of the normalized down-converted IF power (of the circuit using the Gunn diode on Epsilam-10 substrate) as functions of azimuthal and elevation angle of the antenna. For comparison, the RF receiving patterns (dotted lines) of a coaxially fed coupled slot antenna with the same dimensions and measured under the same conditions are also shown. The IF patterns are normalized to the RF patterns. The IF patterns are somewhat distorted compared to the RF patterns. This is due to the additional complexity of the circuit, i.e., the microstrip circuit pattern fabricated at the back side of the substrate, and the incorporation of the mixer diodes inside the coupled slot.

Photographs of the circuits are shown in Figs. 14 and 15.

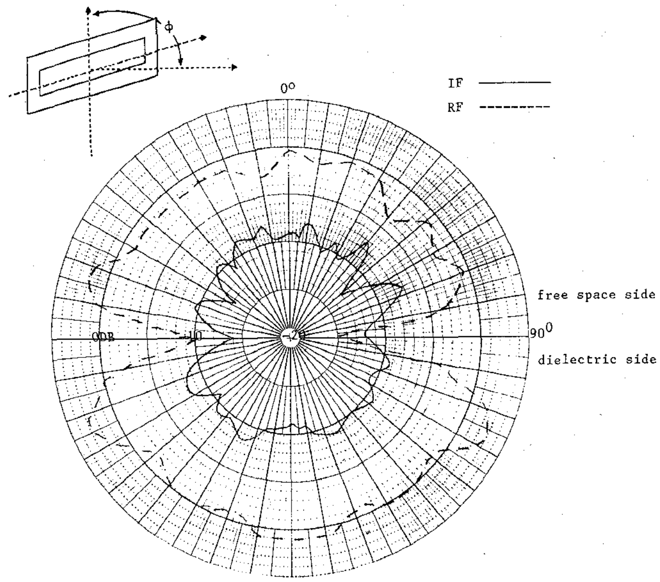

Fig. 13. Relative plots of IF power versus elevation angle f and the coupled slot antenna RF E-plane pattern.

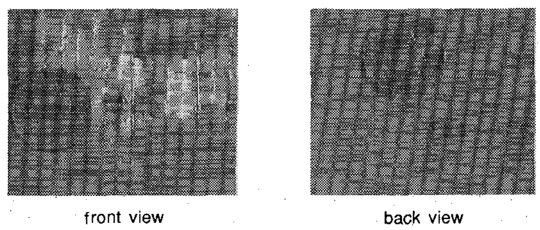

Fig. 14. Receiver circuit using Gunn diode LO (Epsilam-10 substrate).

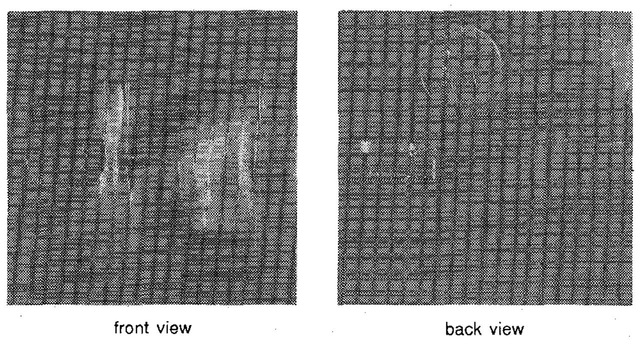

Fig. 15. Receiver circuit using MESFET LO (R/T duroid substrate).

VI. Conclusions

Two quasi-optical designs of integrated planar antenna and receiver front-end circuits have been demonstrated. The circuits have potential applications in receiver arrays as low-cost receiver modules at both microwave and millimeter-wave frequencies. MMIC technology is also potentially applicable for the fabrication of these circuits. When the designs are extended to millimeter-wave frequencies, the dimensions of the circuit need to be scaled down accordingly. For example, if the circuit is to be functioning at 90 GHz on a GaAs substrate, the slot width needs to be reduced to the range of 50 μm. Fabrication of such millimeter-wave quasi-optical receivers can be implemented by the state-of-the-art MMIC technology.

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