Quasi-Optical HEMT and MESFET Self-Oscillating Mixers

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Abstract —**Planar quasi-optical receivers that compactly integrate a coupled slot antenna and a HEMT or MESFET balanced self-oscillating mixer on the same substrate are developed for applications in microwave and millimeter-wave receiver arrays. Both the HEMT and the MESFET circuit are designed and demonstrated at *X*-band. The HEMT circuit exhibits an isotropic conversion gain of 4.5 dB and a noise figure of 6.5 dB at *X*-band. The isotropic conversion gain of the HEMT circuit is 7.5 dB higher than the mixer diode circuit previously reported.**

I. Introduction

QUASI-OPTICAL planar receivers that integrate a coupled-slot antenna, a Schottky diode balanced mixer, and a Gunn or MESFET local oscillator have previously been introduced [1]. These circuits are compact, self-contained units that utilize the orthogonal even-mode/odd-mode characteristic of the coupled slotline (CSL) to achieve intrinsic RF–LO and RF–IF isolation.

In this paper, we present quasi-optical receivers that employ a coupled slot antenna and a balanced HEMT or MESFET self-oscillating mixer. In addition to the favorable features mentioned in [1], the FET (in this paper, FET refers to both HEMT and MESFET) self-oscillating mixer circuits offer two more advantages. First, the new circuits exhibit conversion gain rather than conversion loss, as in the diode mixer circuits reported in [1]. In fact, an isotropic conversion gain of 4.5 dB is achieved for the circuit using HEMT's as opposed to the 3 dB isotropic conversion loss [2] reported in [1]. Second, the new circuits are more compatible with the FET-based MMIC technology since no diodes are used. These compact, self-contained receiver units have potential applications in microwave and millimeter-wave receiver arrays.

Work on MESFET mixers has been reported by many researchers. In general, there are three types of single-gate FET mixer configurations: the gate mixer [3]–[8], the drain mixer [4], [9], and the resistive mixer [10]. In the gate mixer, both the RF and the LO signal are applied to the gate of the device. The MESFET is gate-biased to near pinch-off (Fig. 1). This results in efficient mixing since at this bias condition, the FET's transconductance is most sensitive to the modulation of the externally applied LO signal. In the drain mixer, the RF signal is applied to the gate, and the LO signal is applied to the drain. The device is drain-biased near the knee voltage and is gate-biased to 0 V or a small negative voltage (Fig. 1). At this bias condition, both the FET's output resistance R_o and the transconductance G_m are very nonlinear, and the voltage amplification factor $u = G_m * R_o$ is modulated by the LO signal applied to the drain [9]. The MESFET can also be used as a resistive mixer. In such a mixer, the unbiased channel of the device is used as a time-varying resistor whose resistance is modulated by the LO signal applied at the gate. The MESFET resistive mixer is capable of very low intermodulation owing to the weak nonlinearity of the FET's channel resistance.

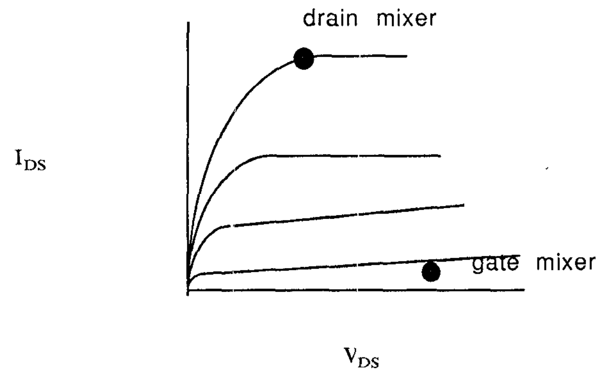

Fig. 1. Bias points of the gate and drain FET mixer.

It has been shown that the MESFET can be used in a self-oscillating mixer circuit where a single device both produces the LO power and mixes the LO with the RF signal [11], [12]. In designing such mixers, care must be taken to prevent the LO signal from being injection-locked to the RF signal. In the present work, a balanced HEMT or MESFET self-oscillating mixer is incorporated with the coupled slot antenna to form a self-contained receiver. These receivers are compact units, and have potential applications in microwave and millimeter-wave receiver arrays. In these self-oscillating mixers, the devices are drain-biased to near the knee voltage, and the gate is not

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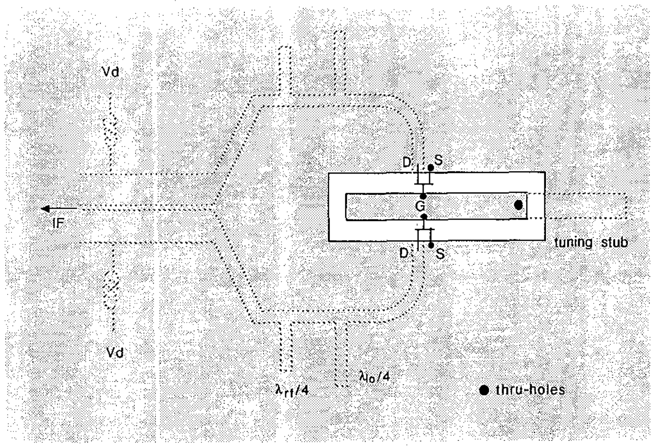


Fig. 2. Circuit layout of the quasi-optical receiver using FET self-oscillating mixer.

biased. This bias condition is similar to that of the drain mixer, and the nonlinearity in both G_m and R_o is utilized for efficient mixing. Since the gate of the device is not biased, the gate bias circuit is eliminated, and the circuit complexity is reduced.

Both HEMT's and MESFET's were used for the receiver circuit. The isotropic conversion gain and the noise figure of the circuit using HEMT's and the one using MESFET's were measured, and the results are compared.

II. Circuit Overview

Fig. 2 shows the layout of the FET self-oscillating mixer circuit. The basic building block of the entire circuit is the connected coupled slot made on the ground plane. The connected coupled slot is used simultaneously as a half-wave resonant antenna for receiving the RF signal in the even mode and as an embedding circuit for the local oscillator, which produces the LO signal, in the odd mode. Due to orthogonality between the even and odd modes of the CSL, the RF signal and the LO signal are intrinsically isolated. This prevents the LO signal from being injection-locked to the RF signal. Packaged NEC 20383A HEMT's and NEC 71084 MESFET's are used. The packaged devices are placed on the backside (microstrip line side) of the substrate. The drain leads of the FET's are connected to the microstrip lines (dotted lines). The gate and the source leads are connected via conducting through holes to the center conductor of the CSL and to the edges of the CSL ground plane, respectively. If FET chips are used or an MMIC fabrication is employed, the FET's can be appropriately placed at the front side of the substrate, inside the coupled slot. The gate and the source terminals would be connected to the center conductor and the ground edges of the CSL, respectively, whereas the drains would be via-hole connected to the microstrip lines.

Fig. 3 shows the RF, LO, and IF signal polarities with respect to the devices. The even-mode RF signal received by the coupled slot antenna is fed to the input ports (gate–source) of the FET's. The two FET's are gate-coupled to produce the LO power in the odd mode. The

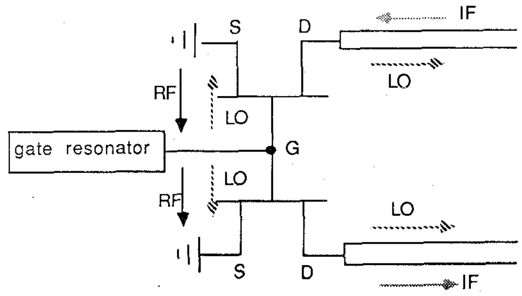


Fig. 3. RF, LO, and IF signal polarities with respect to the FET's.

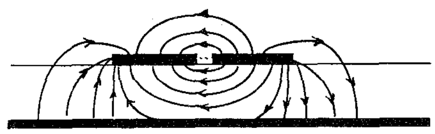


Fig. 4. Electric field pattern of the odd mode of coupled microstrip line.

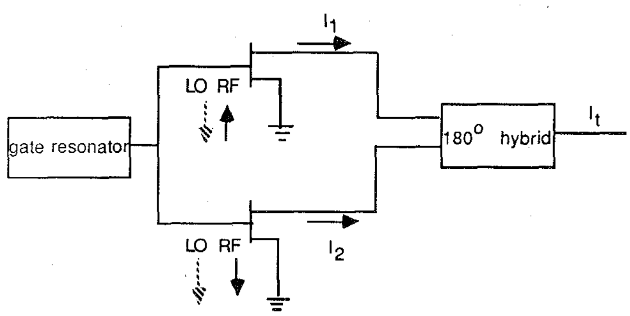


Fig. 5. Currents in a balanced FET self-oscillating mixer.

coupled slot and the microstrip tuning stub (which is connected to the center conductor of the CSL by a conducting through hole) form the gate resonator for the oscillator. The IF signals coming out of the drain ports to the microstrip lines are 180° out of phase. The two microstrip lines are combined to form one coupled microstrip line (CMS). The microstrip lines to CMS line transition functions as a 180° hybrid. The IF signals are power combined at the CMS. The signal is propagated as the odd mode of the CMS. Fig. 4 shows the field pattern of the odd mode of the CMS. The IF signal is coupled out of the circuit by an SMA launcher with the launcher center tap connected to one microstrip and the outer conductor connected to the other microstrip.

The FET self-oscillating mixer is a balanced mixer if the two FET's used are identical. To see this point, the nonlinear relationship between the drain current and the RF and LO voltages is expanded in a power series. With the polarities of the RF and LO signals shown in Fig. 5, the drain currents of the two FET's can be written as

$$I_1 = a(V_{LO} - V_{RF}) + b(V_{LO} - V_{RF})^2 + c(V_{LO} - V_{RF})^3 + \cdots \quad (1)$$

$$I_2 = a(V_{LO} + V_{RF}) + b(V_{LO} + V_{RF})^2 + c(V_{LO} + V_{RF})^3 + \cdots . \quad (2)$$

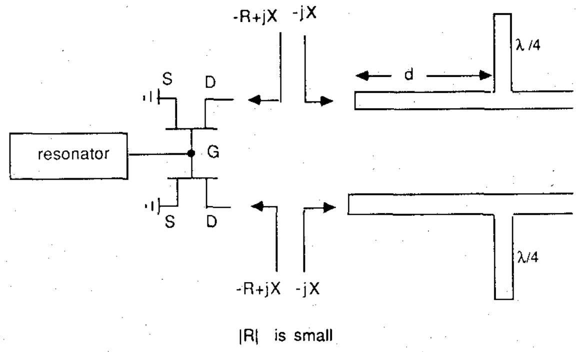


Fig. 6. Schematic diagram of the gate coupled FET oscillator.

The total output current I_t is

$$I_t = I_2 - I_1. \tag{3}$$

By substituting (1) and (2) into (3), it can be shown that the LO signal and the (even, even), (even, odd) terms of the intermodulation products, $mF_{RF} + nF_{LO}$, are rejected at the output port.

III. Circuit Design Principles

The coupled slot antenna dimensions are first determined. The length of the CSL is half a wavelength of the even-mode RF signal frequency. In order to match the coupled slot antenna input impedance to the FET's input impedance, the gate and source leads are connected to the CSL at a small distance from the center of the half-wavelength CSL.

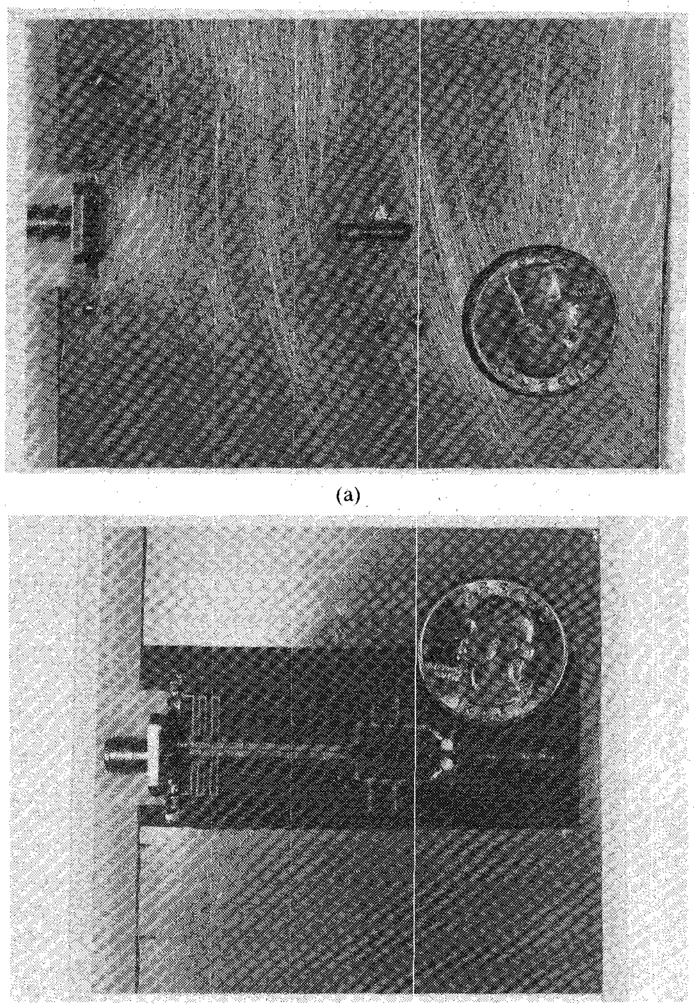
Fig. 6 is a schematic of the oscillator portion of the circuit. The local oscillator is designed approximately by means of the small-signal S parameters of the device. First, the gate resonator is designed by finding the length of the microstrip tuning stub (in Fig. 2), so that at the drain ports the output impedances of the FET's are $-R + jX$, with the value of $|R|$ being small. Then, the length d in Fig. 6 is determined such that the device's drain ports see a reactance of $-jX$ at the oscillation frequency. Under a large-signal oscillation, $|R|$ will be reduced to a small value and will be canceled by the circuit's radiation and other losses.

The IF output impedance of the FET mixer is large. Therefore, the characteristic impedances of the two microstrip lines connected to the drains of the FET's are designed to be 100 W. The two microstrip lines are combined to a coupled microstrip line with an odd-mode characteristic impedance of 50 W.

IV. Circuit Performance

X-band versions of the circuit using HEMT's and the one using MESFET's were fabricated on RT Duroid substrates with a dielectric constant of 2.5 and a thickness of 0.79 mm. Photographs of the HEMT circuit are shown in Fig. 7. The MESFET circuit is essentially the same as the HEMT circuit. To characterize the efficiency of the receivers as a single unit, the isotropic conversion gain, G_{iso}, is used. This quantity is defined as

$$G_{iso} = 10 * \log(P_{IF}/P_{iso}) \quad \text{dB} \tag{4}$$



(a)

(b)

Fig. 7. Photographs of the HEMT circuit. (a) Front. (b) Back.

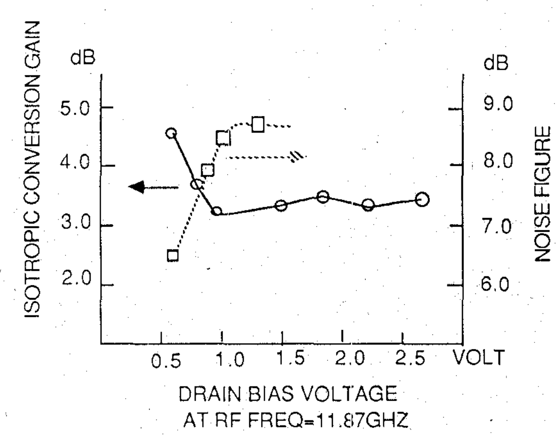


Fig. 8. G_{iso} and noise figure versus bias voltage of HEMT circuit.

where P_{IF} is the down-converted IF power. The quantity P_{iso} is the RF power that would be received if the circuit under test were replaced by an isotropic antenna. Figs. 8 and 9 show the measured G_{iso} versus bias voltage curves for the HEMT and MESFET circuit, respectively. In Figs. 8 and 9, the maximum G_{iso} occurs near the knee voltage of the FET's $I-V$ curves supplied by the manufacturer. Effi-

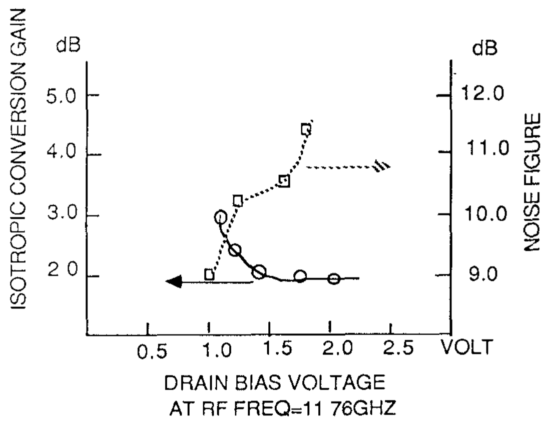


Fig. 9. G_{iso} and noise figure versus bias voltage of MESFET circuit.

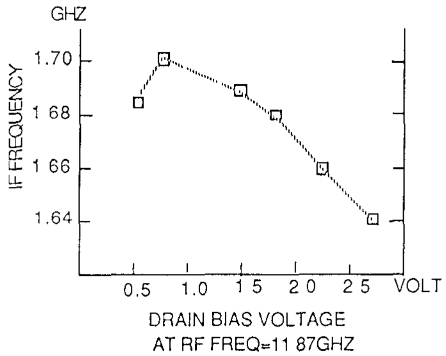


Fig. 10. IF frequency versus bias voltage of HEMT circuit.

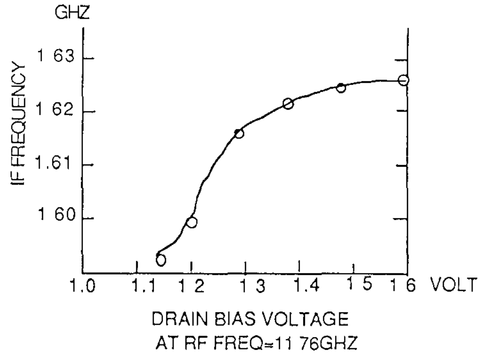


Fig. 11. IF frequency versus bias voltage of MESFET circuit.

cient mixing occurs near the knee voltage because the FET's nonlinearity of concern is strongest at that voltage. The maximum G_{iso} was measured to be 4.5 dB for the HEMT circuit, and 3.0 dB for the MESFET circuit. The 4.5 dB G_{iso} of the HEMT circuit is 7.5 dB higher than the diode mixer circuit reported in [1]. Figs. 10 and 11 show how the IF frequency changes with the bias voltage for the two circuits. The change in LO frequency with bias voltage also affects the conversion characteristic because the usage of quarter-wave stubs makes the circuit narrow-band. However, this effect on the conversion characteristic is secondary because the change in LO frequency is small, as can be seen in Figs. 10 and 11.

The noise figures of the HEMT and MESFET circuits were measured by the hot–cold technique. The measurement setup is shown in Fig. 12. Absorbers folded into cone shapes were used to simulate backbody loads. These two

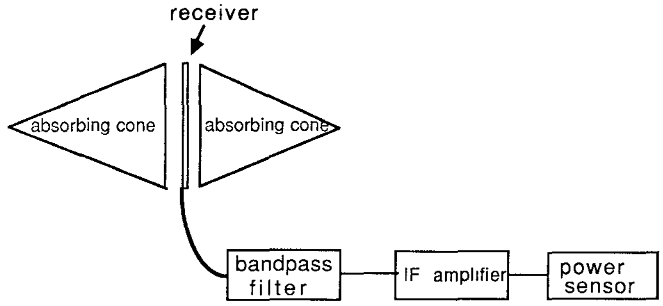


Fig. 12. Noise measurement setup.

absorbing cones cover all of the solid angle seen by the antenna. In the hot measurement, the absorbing cones are at room temperature. In the cold measurement, the absorbing cones are kept at the 77 K temperature of liquid nitrogen. From the noise powers measured at the hot and cold measurements, the receiver noise figure can be extracted by the standard technique. The measured noise figures versus the bias voltages for the HEMT and MESFET circuits are shown in Figs. 8 and 9 along with the isotropic conversion gain curves. The HEMT circuit has the lowest noise figure, 6.5 dB, when the bias voltage is near the knee voltage. For the MESFET circuit, the lowest noise figure is 9 dB. It should be noted that in the balanced self-oscillating mixer configuration, the AM noise produced by the two FET's is canceled if the two FET's are identical. However, this situation is unlikely to occur in practice.

V. Conclusion

Quasi-optical receivers integrating a coupled slot antenna with a HEMT or MESFET self-oscillating mixer are designed and demonstrated at X-band. The circuits are compact, self-contained units, and have potential applications in both microwave and millimeter-wave receiver arrays. MMIC technology is also potentially applicable to the fabrication of these circuits.

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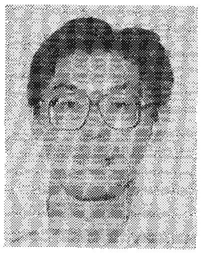

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