Short Papers

X-Band Doubly Balanced Resistive FET Mixer with Very Low Intermodulation

F. De Flaviis and S. A. Maas

***Abstract*—This paper describes a practical realization of a mixer that achieves low intermodulation distortion by using the channel resistance of a GaAs MESFET to provide mixing and achieves even-order spurious response rejection through the use of a doubly balanced structure. Very good results were achieved in terms of second- and third-harmonic levels of −67 and −45 dBC, respectively, at +10 dBm input level. The band-center conversion loss was 11 dB. The circuit was realized in microstrip on an alumina substrate, with a monolithic FET "quad."**

I. Introduction

The design of receivers at microwave frequencies involves several problems, one of which is intermodulation distortion (IM). This problem is critical in receiver front ends, and often it constitutes the fundamental limit to their performance. In the past we have shown [1] how the intermodulation perpformance of a single-device mixer can be improved by using the channel resistance of a GaAs MESFET, instead of a diode, as the nonlinear element. This can be achieved without paying any price in terms of increased noise figure (NF) or conversion loss (L_c). In [1] second- and third-order intermodulation input intercept points (IP_2 and IP_3), respectively, of 28 and 30 dBm on a prototype single FET were achieved.

Other researchers have proposed techniques to improve IM performance. For example, Weiner *et al.* [2] used a doubly balanced mixer similar to ours, and Chang *et al.* made a similar mixer using a GaInAs MISFET [3]. Lepoff and Cowley [4] showed that by slight unbalancing of a balanced mixer, it is possible to obtain certain cancellations in the IF current. However, we have found that the use of a GaAs MESFET generally achieves better IM performance. In order to obtain the maximum rejection of even-order spurious responses, a doubly balanced structure has been used [5]. Particular attention was devoted to the design of the LO, RF, and IF baluns in order to minimize the complexity of the layout and to avoid transmission-line crossings or via holes in the circuit; these introduce parasitics and may degrade the performance of the mixer. A monolithic FET "quad" provided good matching between individual FETs, and thus helped achieve good balance. These efforts resulted in a mixer having IM performance substantially exceeding that of previously published circuits.

II. Device Characterization

The doubly balanced mixer used the chip shown in Fig. 1. The chip, realized on a 100-μm GaAs substrate, consists of four FET's in a ring configuration, each FET having a gate length and width of 0.5 and 300 μm, respectively. The chip was produced by TRW, Inc., Space and Electronics Group.

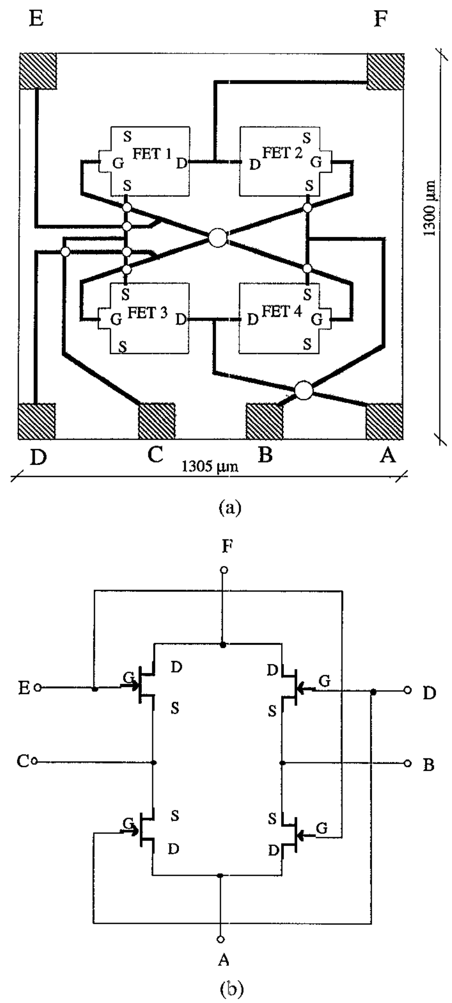

Fig. 1. Four-FET chip used for the fabrication of the mixer. (a) Chip layout. (b) Circuit. The chip is realized on a GaAs substrate of thickness 100 μm and the FET's channels are 0.5 × 300 μm

The Curtice model [6] was used to model the FET's I/V characteristics. As a model adequate for predicting IM performance of this type of mixer does not yet exist, the goal was to use the model only for designing matching circuits and predicting conversion loss. The relation for the drain current is

$$I_d = \left(A_0 + A_1 V_1 + A_2 V_1^2 + A_3 V_1^3\right)\tanh(\gamma V_d) \tag{1}$$

where, in general,

$$V_1 = V_g(t-\tau)(1+\beta(V_{ds0} - V_d)) \tag{2}$$

β is the pinch-off coefficient, determined empirically. Resistive mixers operate in the linear region of the FET, where $V_{ds} \approx 0$, so (2) becomes

$$V_1 = V_g(t-\tau) \tag{3}$$

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TABLE I
FET PARAMETERS

Parameter	Value
A_0	0.3343
A_1	0.4045
A_2	0.1234
A_3	0.001
γ	1.0
R_g	2.0
R_d	1.3
R_s	6.7
C_{gs0}	0.191
C_{gd0}	0.140

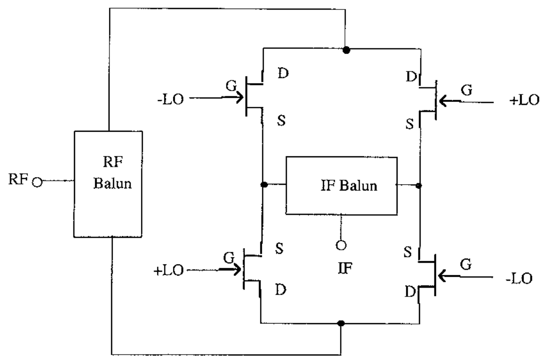

Fig. 2. Circuit of the mixer.

where τ is the time delay for the device. With a channel length of 0.5 mm, we estimate $\tau = 2$ pS [7]. Values of other model parameters were found by fitting to measured I/V characteristics, and the elements in the FET's equivalent circuit were found by fitting to S parameters measured from single devices on the same wafer as the "quad." The results are given in Table I.

R_g, R_d, and R_s are the gate, drain, and source series resistances, respectively. The gate-to-source and gate-to-drain capacitances C_{gs} and C_{gd} are modeled as simple depletion capacitances:

$$C_{gs} = \frac{C_{gs0}}{\sqrt{1 - \frac{V_{gs}}{\phi}}} \tag{4}$$

$$C_{gs} = \frac{C_{gd0}}{\sqrt{1 - \frac{V_{gd}}{\phi}}} \tag{5}$$

No other elements are used in the FET's equivalent circuit.

The use of a four-FET chip instead of four discrete FET's avoids bridges or crossings in microstrip and provides a layout for the mixer that can be readily realized in monolithic form. Also the four FET's in the chip have nearly identical I/V and C/V characteristics; this is essential for the balance of the structure.

III. Circuit Design

The main goal of this effort is to obtain low intermodulation distortion, principally the second and third harmonics of the IF. These products may be viewed as spurious responses, the second harmonic being a (2, −2) response and the third a (3, −3). (Here we use conventional notation for spurious responses, where an (m, n) response is one for which $f_{\text{IF}} = mf_{\text{RF}} + nf_{\text{LO}}$.) These products are generally greater in magnitude for a given RF excitation level, than conventional multitone spurious responses such as the infamous $2f_{\text{RF1}} - f_{\text{RF2}}$. According to simple power series theory [8] the second-harmonic response is 6 dB greater than the second-order, two-tone response, and the third-harmonic response is 9.5 dB greater than the third-order two-tone. Although in real circuits these differences are often not precisely observed, in our experience they are usually roughly correct. The IF harmonics do, however, depend upon circuit and device characteristics in the same way as multitone IM products [9]; thus, a mixer exhibiting good performance in terms of these harmonic IM products will, in all but the most irregular circumstances, exhibit good multitone IM characteristics as well.

It is important to use a circuit topology that rejects even-order spurious responses. The topology chosen is the balanced ring mixer described by Weiner [2]. This structure is shown schematically in Fig. 2. By using this circuit, we obtain the advantages of the doubly balanced structure: rejection of the local oscillator (LO) AM noise and spurious responses involving even LO or RF harmonics.

The RF and IF baluns, as well as the symmetry of the FET ring, provide isolation between the LO, RF, and IF ports. This is particularly important in FET resistive mixers because of the relatively large capacitance between the gate and drain when the FET is biased at $V_{ds} = 0$.

A schematic layout of the mixer is shown in Fig. 3. The mixer was realized by 3-μm gold microstrip on an alumina substrate of 0.635 mm thickness, with a dielectric constant of 9.8. The LO frequency is 10 GHz, the RF is 12.4 GHz, and the IF is 2.4 GHz. The LO balun is realized with a simple phase shifter of 180 degrees, since no isolation is required between the two arms of the shifter. We used a microstrip Y junction [10] instead of T junction to guarantee the maximum degree of symmetry between the two arms of the balun. Through the LO balun we also provide gate bias to the FET's, −1.9 V to −3.7 V. The optimum compromise between intermodulation performance and conversion losses was found to be at $V_{gs} = -2.96$ V.

The RF balun was realized as a modified rat-race of $3\lambda/4$ and $5\lambda/4$ instead of the customary $\lambda/4$ and $3\lambda/4$ sections in order to use larger and more practical dimensions. Although this costs some bandwidth, it allows the 50-ohm termination and a radial stub to be placed directly inside the ring. The IF balun is a planar version of a modified Marchand balun [11]. Although this multistrip balun required some air bridges, the IF was low enough that these were acceptable. All the baluns were fabricated and tested separately before use in the mixer.

IV. Performance

This prototype mixer was tested under two different conditions. In the first, we measured the bandwidth and the port-to-port isolation without any external circuit. In the second set of measurements we used a set of filters to minimize the effects of harmonics of the LO and RF test signals. From the first set of measurements we found that the mixer has a bandwidth of approximately 2 GHz. The isolation between the ports of the mixer, without any external filtering, was about 35 dB.

Fig. 4 shows the behavior of the second- and third-order IM obtained by varying the RF power and utilizing an LO signal of 21.5 dBm and reverse gate-to-source bias of 2.96 V. We observe that for reasonable values of RF power (below 10 dBm) the third-order intermodulation is below −45 dBC, and the second-order IM level is below −67 dBC.

The behavior of the second-harmonic (4.8 GHz) and third-harmonic (7.2 GHz) power levels, with variation of the LO power, is shown in Fig. 5. The RF level is +10 dBm.

It is interesting to note that the IM levels shown in Fig. 4 do not display the n dB/dB slope usually observed for nth-order IM. This is not unusual in very-low-distortion mixers. It is caused by the inter-

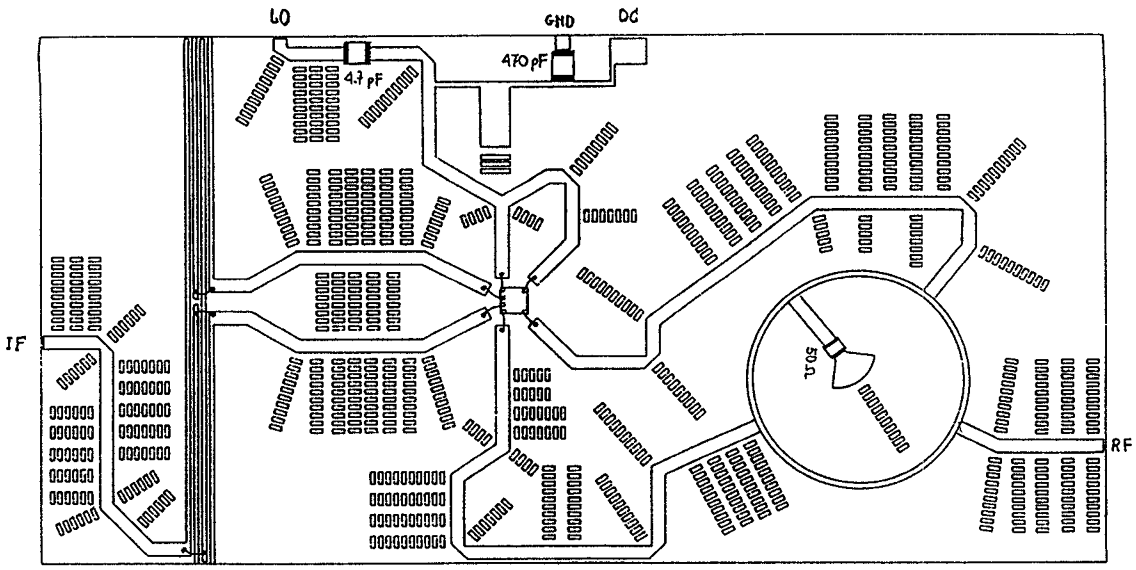

Fig. 3. Circuit layout of the mixer.

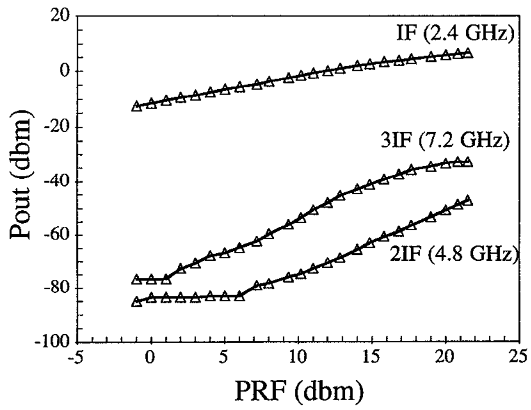

Fig. 4. Fundamental, second IF harmonic, and third IF harmonic of the mixer. LO power is 21.5 dBm and dc gate bias is −2.96 V.

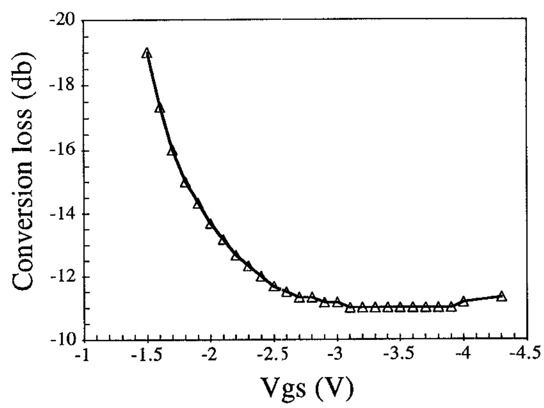

Fig. 6. Conversion loss as a function of the reverse gate bias, with LO power level of 21.5 dBm.

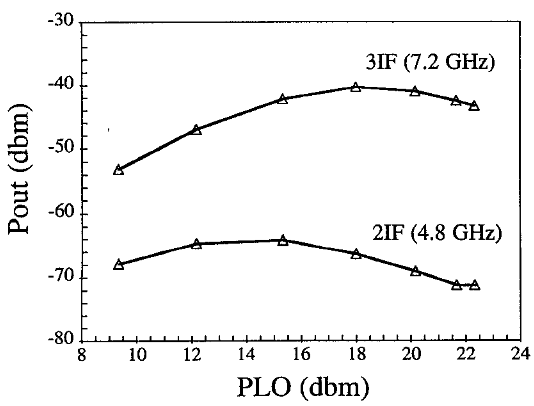

Fig. 5. IM levels as a function of LO power at optimum dc bias. RF level is + 10 dBm. Filter are used at the RF and LO ports to minimize effects of harmonics of the RF and LO sources.

ference of higher-order IM products that occur at mixing frequencies normally associated with lower-order products; for example, when the third-order IM levels are very low and the RF level is very high, the 5th-order product at $4f_{\mathrm{IF}} - f_{\mathrm{IF}}$ may interfere with the third-order product at $3f_{\mathrm{IF}}$. It is possible that the n dB/dB slope might exist at lower RF levels, because the high-order interfering products would decrease more than the low-order. However, we were unable to measure the IM at RF levels below 0 dBm.

The behavior of the conversion loss as the gate bias is varied is shown in Fig. 6. Good conversion loss is obtained with reverse bias voltage between −2.9 and −3.8 V.

V. Conclusion

This paper shows that a doubly balanced mixer based on the resistance of a GaAs MESFET channel can achieve low second- and third-order intermodulation. The IM performance was shown to be sensitive to out-of-band terminations at its ports. Because this circuit topology rejects second-order responses, the second-order IM performance is especially good. Unfortunately, the LO power required by this mixer is relatively high, due to the fact that four FET's must be pumped. Also, special attention was devoted to the design of the baluns to avoid crossings or microstrip via holes. The prototype was completely planar, so realization as a monolithic circuit is possible.

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REFERENCES

[1] S. A. Maas, "A GaAs MESFET mixer with very low intermodulation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, p. 425, Apr. 1987.

[2] S. Weiner, D. Neuf, and S. Spohrer, "2 to 8 GHz double balanced MESFET mixer with +30 dBm input 3rd order intercept," *IEEE MTT-S Int.Microwave Symp. Dig.*, p. 1097, 1988.

[3] K. W. Chang, B. R. Epstein, E. J. Denlinger, and P. D. Gardner, "Zero bias GaInAs MISFET mixers," *IEEE MTT-S Int. Microwave Symp Dig.*, p. 1027, 1989.

[4] J. H. Lepoff and A. M. Cowley, "Improved intermodulation rejection in mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, p. 618, Dec. 1966.

[5] S. A. Maas, *Microwave Mixers.* Norwood, MA: Artech House, 1986.

[6] W. R. Curtice and M. Ettenberg, "A nonlinear GaAs FET model for power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, p. 1383, Dec. 1985.

[7] A. S. Grove, *Physics and Technology of Semiconductor Devices.* New York: Wiley, 1967.

[8] D. D. Weiner and J. F. Spina, *Sinusoidal Analysis and Modeling of Weakly Nonlinear Circuits.* New York: Van Nostrand, 1980.

[9] S. A. Maas, "Two-tone intermodulation in diode milpxers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, p. 307, Mar. 1987.

[10] T. C. Edwards, *Foundations for Microstrip Circuit Design.* New York: Wiley.

[11] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines.* Norwood, MA: Artech House, 1987.

Analysis of an Array of Four Microstrip Patch Resonators Printed on an Anisotropic Substrate

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***Abstract*—The spectral-domain approach is applied to the analysis of a four microstrip patch resonator array that is printed on anisotropic substrate. Basis functions are carefully chosen to accurately represent the current distribution on each patch, corresponding to every symmetry of the structure. Ample numerical results are presented which show the effects of geometrical and anisotropic medium parameters on dominant resonant frequencies of the microstrip patch array.**

I. INTRODUCTION

Electromagnetic properties of anisotropic materials have been recently investigated in many important applications, including microwave and millimeter wave integrated circuits [1], microstrip antennas [2], and microstrip resonators [3]. To efficiently formulate boundary-value problems in wave propagation involving both isotropic and anisotropic media, several variations of matrix representation to Maxwell's equations have been proposed [4]–[7].

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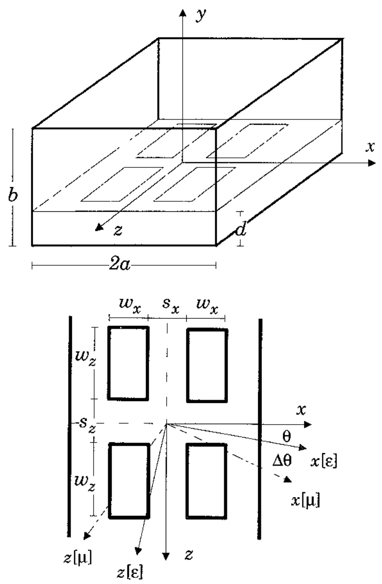

Fig. 1. Geometry of a four microstrip patch resonator array.

In this paper, the spectral domain approach and matrix operators are employed to analyze four patch resonator arrays that are printed on anisotropic substrates. Microstrip patch resonators find important applications in MICs as resonant elements of oscillator and filter circuits. Anisotropic nature of the substrate allows an added degree of freedom in the design of the array. It allows for electronic rather mechanical tuning of the resonator by changing the applied biasing dc field. The existing literature dealing with this subject is rather limited [3], thereby providing motivation for this work.

The resonator problem is formulated in the spectral domain in terms of two components of the E-field that are tangential to the substrate interface. The remaining field components are obtained from Maxwell's curl equations. To calculate resonant frequencies efficiently, basis functions for the currents on all four patches are systematically constructed to represent even-even, even-odd, odd-even, and odd-odd modes. Dominant resonant frequencies are computed for different geometrical and substrate material parameters, showing their effect on each mode.

II. FORMULATION OF THE RESONATOR PROBLEM

Consider four rectangular patches with dimensions, (w_x, w_z), and separated by (s_x, s_z), that are printed on an anisotropic substrate enclosed within a rectangular waveguide shown in Fig. 1. The substrate is characterized by $[\varepsilon]$ and $[\mu]$ tensors whose xy, yx, yz, and zy elements are zero, but it includes missaligned with the x and z axes of the resonator (see Fig. 1) [8].

To formulate the boundary-value problem in the spectral domain, the following 2D Fourier transform is employed:

$$\tilde{\xi}(\alpha_n, y, \beta) := \int_{-\infty}^{-\infty} \int_{-a}^{a} \xi(x, y, z) e^{j\alpha_n x + j\beta_z} dx dz. \qquad (1)$$

Unlike [9] where isotropic substrates are considered, herein, summation index n takes on all integer values from minus to plus infinity due