Broadband GaAs MMIC Downconverter with very Low Intermodulation for TV Applications

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Abstract

A novel combination of a packaged GaAs MMIC with a microstrip-coupled slot high performance 180° hybrid constitutes a downconverter, which provides the very low intermodulation level required by some TV applications. The packaged chip was mounted on a substrate together with a high performance and seldom-used MIC 180° hybrid. No adjustable filters are required due to the broadband behavior of the whole downconverter. This feature is required for cost reduction. A double-balanced mixer and the LO balun have been integrated in the same chip. A properly biased cold FET was used in the mixer to achieve low distortion frequency mixing. An active phase splitter was chosen as the LO balun in order to get small phase errors over a wide frequency band. The MIC 180° hybrid, which makes use of microstrip lines, slot lines and coupled-slot lines, was used as the RF balun. The topology used for this hybrid makes it very useful for balanced mixers, since there is no crossing of MIC transmission lines. On the other hand, there are no active elements, so no distortion is added to the downconverter. The hybrid was designed with an intensive use of a quasy-planar electromagnetic simulator. MMIC package modeling is also discussed in the paper. The MMIC was fabricated using the F20 process of the GEC Marconi foundry. Conversion losses of 8.5 dB can be obtained for the whole downconverter with a LO drive of 5.5 dBm. A 3rd order intercept point of 21 dBm of output power and a spectral purity in the complete RF frequency band of more than 70 dB were achieved.

I.INTRODUCTION

Mixers are usually the most nonlinear devices of a receiver front end. For this reason, the intermodulation (IM) performance is often limited by that of the mixer, and furthermore, this device is the only stage that generates spurious signal responses. For TV applications, these characteristics may be more limiting than noise, since broadband behavior is required for the receivers. On the other hand, low intermodulation levels are required in some digital systems (like OFDM modulation systems), which has led to an improvement in the distortion level of the mixers. Some methods of achieving better IM mixer performance can be found in the literature (1), (2). Recently, resistive mixers have been studied by several authors (3, 4), using the FET as a variable resistance element with no drain bias. The channel resistance of an unbiased GaAs MESFET is only weakly nonlinear. The unbiased channel operates as a simple resistor whose value can be varied by the gate voltage. This kind of mixer generates very low intermodulation and is capable of high output power at moderate LO levels. This paper describes the design and performance of a MMIC downconverter, which is made up of a double-balanced mixer and a balun for the LO signal. A ring configuration, using FETs without biasing, was chosen for the mixer. A differential amplifier was used as the LO balun, in order to avoid large-input power level for the LO signal. A MIC 180° hybrid was used as a balun for the RF signal. This circuit makes use of a combination of microstrip lines, slot lines and coupled-slot lines and, since there is no need of transmission line crossing, it is very suitable for balanced mixers. As there are no active elements, no distortion is added. This last feature, together with small losses, constitute the main advantages of this circuit.

II. DESIGN OF THE RF BALUN

A 180° phase shift happens when two microstrip-to-slotline transitions are connected back-to-back. This can be explained by considering the electric field distribution associated with the microstrip-slotline transition. This phase-change is independent of frequency (at least in a first order analysis) and thus, it can be used in broadband circuits.

In order to adjust this circuit to get the best performance, the Momentum Planar Electromagnetic Simulator, included in MDS software from Hewlett-Packard, was used. The HP Momentum simulator uses a numerical procedure, based on the Method of Moments, to simulate passive circuits. This simulator is specifically designed for planar circuits and becomes a very useful design tool when a circuit model does not exist for an arbitrary shape. The Momentum module takes into account the coupling between lines in the same or different levels, which is very important in our case, since it is not possible to simulate the coupling between microstrip lines and slot lines using a circuit model. The Momentum engine requires the circuits to be introduced in layout form (planar geometry) which means a saving in time since this format (layout) is also used to fabricate the circuit.

Fig. 1 shows simulation results for this balun. The first figure represents the input port matching, being better than 10 dB for the optimized band. Less than 4 dB coupling was predicted over more than 1.5 GHz frequency band. The simulations were performed from 0.5 to 3 GHz, although the circuit was optimized at 1.885 GHz (RF frequency). Finally, the isolation between the two input ports is predicted to be more than 35 dB in the whole simulated frequency band. Fig. 2 shows the phase difference between the outputs when the input signal is applied to the E port, where less than 0.5° phase error has been obtained for the frequency of interest (1.885 GHz). As can be seen from these figures, the circuit shows a broadband performance, only limited by the quarter wavelength slot and microstrip lines.

Epsilam-10 was used as a substrate to fabricate the circuit. In order to validate the electromagnetic simulator, this balun was measured alone as a first version. Measurement results have been included with simulations, showing excellent agreement, as can be seen in Figs. 1 and 2. In the final version, the balun was not included in the MMIC for cost and size reasons, as can be seen in IV.

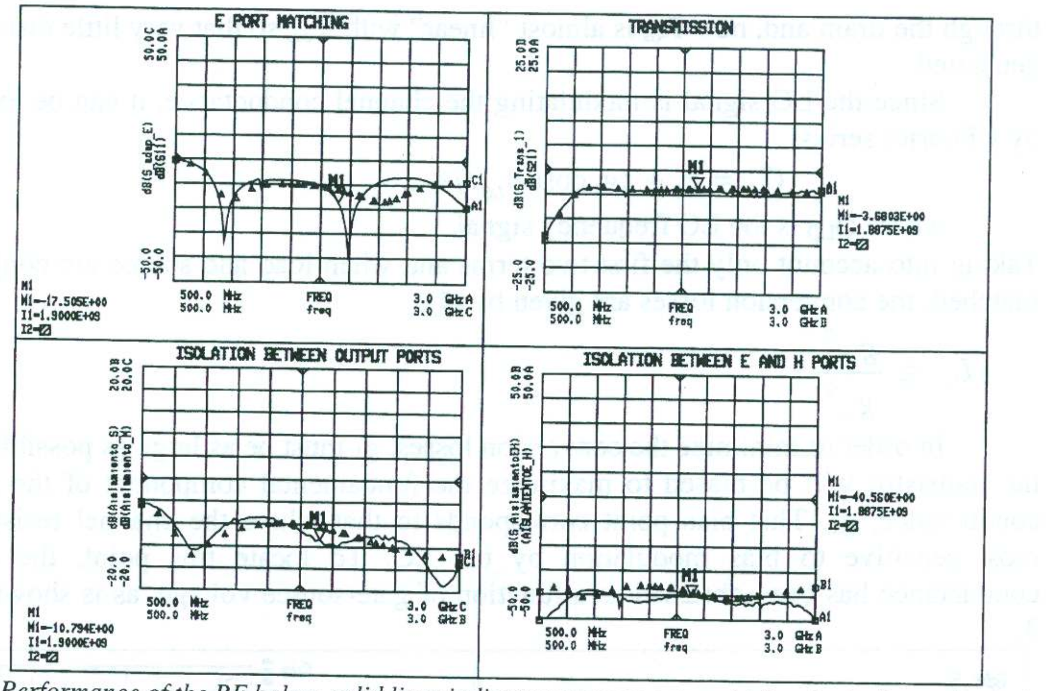

Fig. 1 Performance of the RF balun: solid lines indicate measurements and triangles indicate simulations

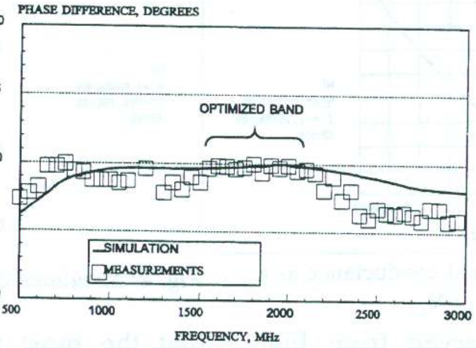

Figure 2: Phase difference between the outputs

III. DESIGN OF THE MMIC

The downconverter is made up of the RF balun, which was explained above, and the LO balun as well as by the mixer. Monolithic implementation was chosen for the last two circuits, which were both integrated in the same chip.

A differential amplifier was used as the LO balun, since accurate phase shifts can be achieved, as well as an amplification of this signal, which avoids the need to use large levels of LO drive. Two stages were cascaded in order to minimize the phase errors in the LO frequency band.

For the mixer, a double-balanced structure was chosen to achieve accurate isolations. No drain bias was used for the mixer transistors in order to generate the lowest possible level of distortion. The channel resistance of a cold MESFET can change when a signal is applied to the gate terminal. If the transistor is drain biased with a very small (or zero) voltage then, the relation drain to source current versus gate-source voltage is non-linear. However, drain-source current is almost linear with drain-source voltage. This last characteristic permits a very small distortion level compared to that generated by a diode. Since the channel resistance is non-linear with V_{gs}, the LO signal must be applied between these two terminals. The RF signal will be injected through the drain and, now R_{ds} is almost “linear” with V_{ds}, so that very little distortion is generated.

Since the LO signal is modulating the channel conductance, it can be expanded by a Fourier series:

$$G_{ds} = g_0 + 2g_1 \cos(\omega_{LO} t) + \dots \tag{1}$$

where ω_{LO} is the LO frequency signal.

Taking into account only the first two terms and when load and source are conjugately matched, the conversion losses are given by (4):

$$L_c \cong \frac{g_0^{\;2}}{g_1^{\;2}} \tag{2}$$

In order to minimize the conversion losses, g_1 must be as large as possible. Thus, the transistor will be biased to maximize the fundamental component of the channel conductance, g_1. This bias point corresponds to that where the channel resistance is most sensitive to bias modulation by the LO. To locate this point, the channel conductance has been obtained as a function of gate-source voltage, as is shown in fig. 3.

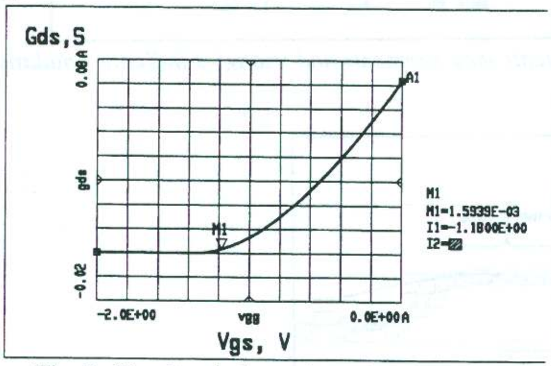

Fig. 3: Simulated channel conductance as a function of V_{gs}

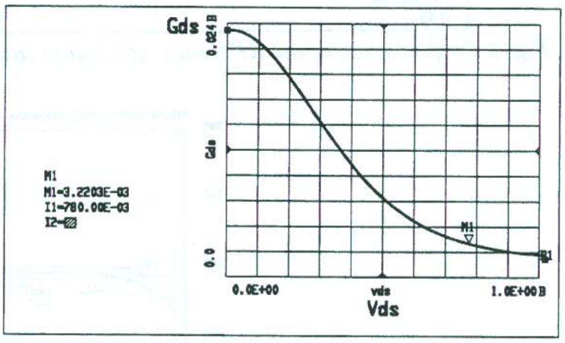

Fig. 4: Simulated channel conductance as a function of V_{gs}

It can be observed from Fig. 3 that the most non-linear region occurs at approximately V_{gs} = -1.2 V, a little above the pinch-off point.

Since RF signal is injected through the drain, the channel resistance must show a very linear drain-bias dependence. Fig. 4 is a plot of the channel conductance as a function of drain-source voltage. For dc-bias lower than 0.5 V, the variation is almost linear, and very little distortion will be produced.

The third-order derivative of the drain-source current with V_{ds} as a function of V_{ds} has been obtained. This graph is very important for the third-order intermodulation and can help us to find the best value for V_{ds} in order to get be lowest intermodulation level. Since drain-gate capacitance is greater for non-biased transistors compared with the same transistor in the saturation region, there is a coupling between these ports. Therefore, LO signal leakage will appear in the drain, increasing the drain-source voltage and the intermodulation level generated.

A low DC value (<0.5 V) at drain port can be obtained by shorting the terminal at LO frequency. Nevertheless, balanced topologies must be used for broadband applications in order to obtain good isolations between ports. A ring MESFET mixer was used in this case, since LO and RF frequency bands are very close. The LO signal is injected at the gates and RF at the drains, while IF signal is extracted from the source terminals. The chip was packaged in a ceramic case and mounted on a duroid substrate. Fig. 5 shows a photograph of the MMIC including the mixer and the LO balun.

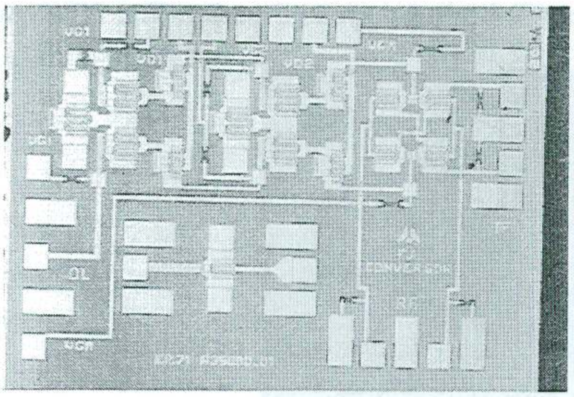

Fig. 5: Photograph of the MMIC

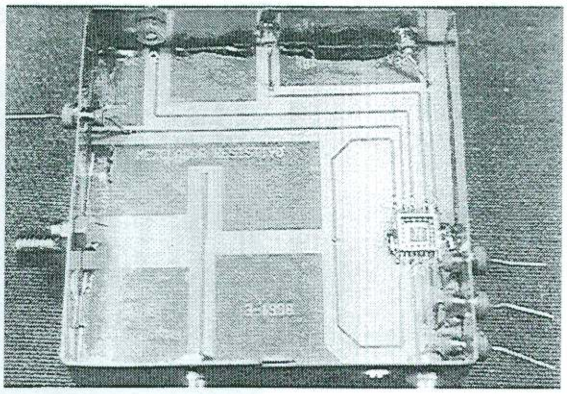

Fig. 6: Photograph of the complete downconverter

The harmonic balance technique, available in the HP MDS program, was used to simulate the mixer. The parasitic effects of the package have been taken into account in the simulations with a proposed equivalent circuit model. A ceramic case was chosen in this case, but a plastic one can be also used. The results of the RF balun, obtained from Momentum, can be incorporated in this program to predict the performance of the whole upconverter. Fig. 6 shows a photograph of the downconverter. The mixer and the LO balun were fabricated using the GEC Marconi F20 foundry process, which employs 0.5 µm gate-length MESFET. The mixer and the LO balun were integrated in a 3.5 mm^2 chip. The packaged chip and the RF 180° hybrid were mounted in the same circuit as can be seen in Fig. 6.

IV. MEASUREMENTS OF THE UPCONVERTER

A spectrum analyzer (HP70000 system) was used to measure the circuit. Although a frequency of 1.8 GHz was used for the RF signal since this value is a typical intermediate frequency in tuners used to reallocate TV signals, the input frequency band is only limited by the passive balun (see II), whose circuit has more than 1 GHz bandwidth. The output frequency can be chosen among any VHF or UHF channel.

Fig. 7 shows the conversion losses of the whole converter as a function of the output frequency for a LO input power of 5.5 dBm. Simulation results were added in the same figure, showing good agreement with measurements.

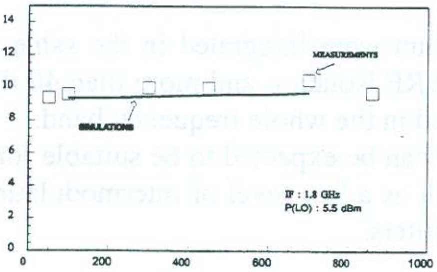

Fig. 7: Conversion losses vs. RF frequency

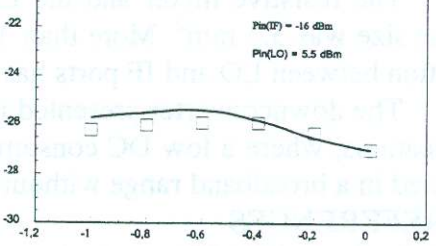

Fig. 8: Output power vs. mixer gate voltage

For an input power of –16 dBm, output power is shown in Fig. 8 along with simulations, as a function of mixer gate voltage. There is a mixer gate voltage value, where the second order intermodulation in the single tone test is diminished until obtaining 70 dB of spectral purity for –17 dBm of output power. For broadband applications the second-order intermodulation causes a lot of problems, since these products can not be filtered and therefore will limit the spectral purity. Fig. 10 shows the output spectrum in this case, for a 100 MHz IF signal.

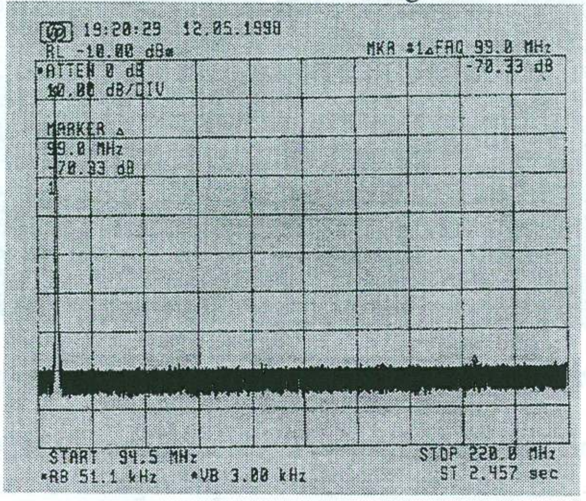

Fig. 10: Output spectrum of the downconverter

The two-tone test was used to characterize the third-order intermodulation performance of the downconverter. A third-order interception point of 20 dBm of output power was measured, which confirms the low distortion generated by this mixer.

The isolation between LO and output (RF) ports is greater than 30 dB, and more than 40 dB between IF input and RF output ports.

V. CONCLUSIONS

A low intermodulation downconverter has been developed, by making use of coupled slot lines for the MIC RF balun and a resistive double-balun MMIC mixer. The resistive mixer performance is not degraded by the RF balun thanks to the low losses and the small phase error obtained. A third-order interception point of 21 dBm of output power has been reached with only 5.5 dBm LO input power. 70 dB of spectral purity was achieved over the whole RF frequency band with –17 dBm of output power, which shows the high linearity of the downconverter.

A novel design method has been employed to solve the specific structure formed by the microstrip, slot and coupled slot lines. This method uses a special module and makes it possible to predict the behavior of this balun with excellent agreement between simulated and measured results.

The resistive mixer and the LO active balun were integrated in the same chip whose size was 3.5 mm^2. More than 30 dB of LO/RF isolation and more than 40 dB of isolation between LO and IF ports has been reached in the whole frequency band.

The downconverter presented in this paper can be expected to be suitable for TV applications, where a low DC consumption as well as a low level of intermodulation is required in a broadband range without adjustable filters.

VI. REFERENCES

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