A Monolithic AlGaAs/InGaAs Upconverter IC for K-Band Wireless Networks

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Abstract—**This paper concerns with the design consideration, fabrication process, and performance of a CPW heterojunction FET (HJFET) upconverter MMIC for K-band wireless system applications. To realize a mixer featuring a simple structure with inherently isolated ports, and yet permitting independent port matching and low LO power operation, a "source injection" concept is introduced by treating the FET as a three-port device in which the IF and LO signals are, respectively, applied to the gate and source terminals, and RF signal is extracted from the drain terminal. The upconverter chip incorporates an HJFET as a mixing element, an IF matching network, an LO matching network, an RF matching network, and an output filter. The upconverter can operate with an LO power level as low as −16 dBm for IF signals in 1.5–2.5 GHz band, and LO signals in 20–23 GHz band. Including a 3 dB pass-band insertion loss of the filter, the upconverter exhibits a maximum conversion gain of −6 dB for an IF power of −5 dBm at 1.9 GHz, and an LO power of 10 dBm at 21.5 GHz. LO suppression at IF and RF ports, respectively, is better than 22 dB and 20 dB, and IF suppression at RF port is better than 35 dB.**

I. Introduction

REBIRTH OF WIRELESS technology and its application to a variety of systems including local area networks, mobile computers, and intelligent highways have urged development of low-cost small-size low-power K-band, V-band, as well as W-band fully monolithic transceiver modules with 1–2 GHz IF frequencies, for facilitating 100–200 Mbps transmission of data, voice, and video [1]–[4]. In a transceiver module, mixers are key-elements for frequency conversion, and require rigorous design methods to achieve an optimum operation. It is desirable to develop mixers featuring a simple structure with inherently isolated ports, and yet permitting independent port matching and low LO power operation.

Conventional FET mixers employ either a "gate mixing" [5], [6] or a "drain injection" [7], [8] topology to produce a desired frequency component, by applying the LO signal to the gate terminal or drain terminal of the device, respectively. In such a structure, since LO signal shares the same port with IF (or RF) signal, independent port matching for each signal is impossible, and to achieve a sufficiently high isolation between LO signal and IF (or RF) signal, usually hybrid circuits such as Lange couplers, power dividers as well as balun circuits and several anti-phase input signals are required [9]–[12] which totally increase the mixer circuit complexity. Moreover, since in such a circuit topology the effect of LO signal on the FET transconductance modulation is small, LO signals with high power level are required to perform a satisfactory mixing operation.

Introducing a "source injection" concept, and treating an FET as a "three-port device," the present paper describes a class of FET mixers for realization of microwave and millimeter-wave frequency converters which exhibit a simple structure and possess the above features.

Circuit design, fabrication process, and experimental results for the case of a K-band upconverter using a $0.15\mu m \times 200$ μm AlGaAs/InGaAs heterojunction FET are presented.

II. Circuit Design

A block diagram and corresponding equivalent circuit for the CPW K-band upconverter are shown in Fig. 1. The upconverter incorporates an HJFET as a mixing element. IF signal with a frequency of f_{IF} is applied to the gate terminal through the IF filtering and matching network, and LO signal with a frequency of f_{LO} is applied to the source terminal through the LO filtering and matching network. On the other hand, a resultant upper sideband RF signal having a frequency of $f_{LO} + f_{IF}$ is extracted from the drain terminal, after passing through the RF matching and filtering network and the filter. Use is made of spiral inductors in the IF matching network for resonant type filtering and IF frequency matching. The RF filter consists of two T-type networks connected in parallel for suppressing the lower sideband frequency ($f_{LO} - f_{IF}$) and LO frequency (f_{LO}), but passing upper sideband frequency ($f_{LO}+f_{IF}$). The LO matching network is essentially responsible to provide an unconditionally stable operation for the upconverter, both in the presence and absence of an LO signal. The short-circuited transmission line $L5$ in the LO matching network facilitates transistor's gate and drain dc biasing.

This structure utilizes the inherent isolation characteristics of the FET terminals under the pinch-off condition to separate the IF, LO, and RF signals without necessity of any hybrid circuit. In the present structure, since the LO signal is directly applied to the source terminal, it has the largest effect on the device transconductance modulation and, consequently, on nonlinear mixing enhancement, which facilitates a low LO power operation.

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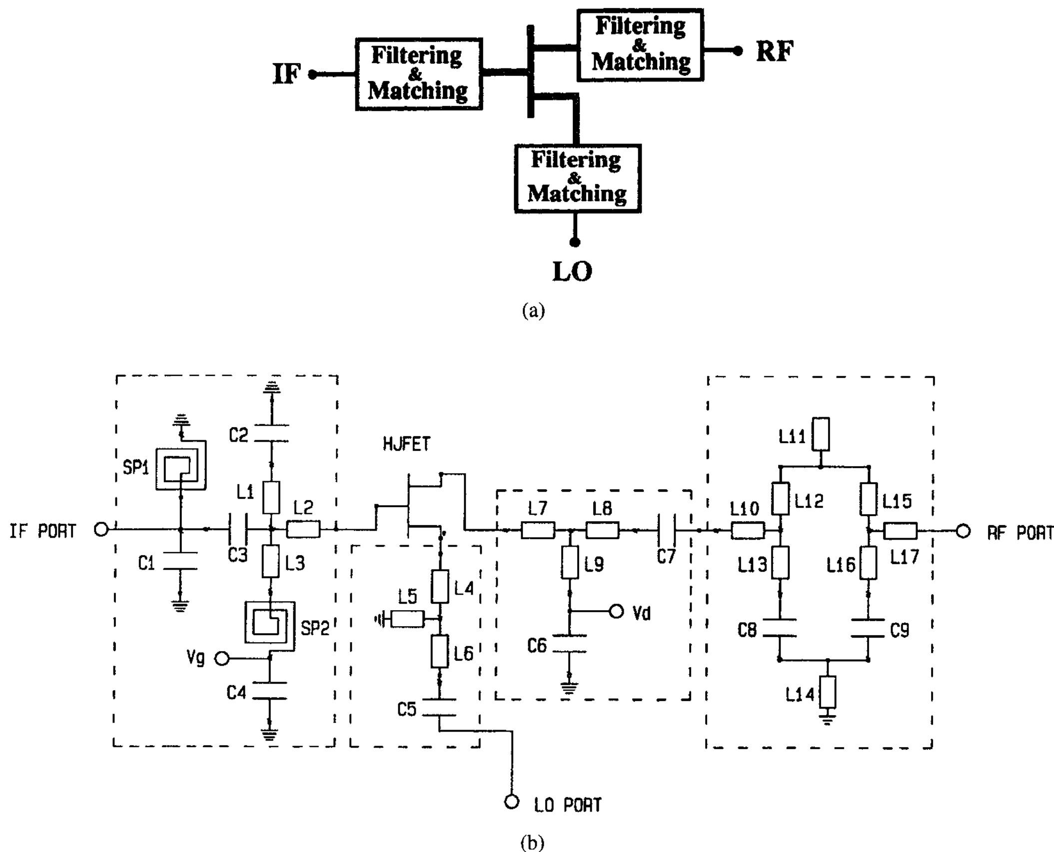


Fig. 1. K-band upconverter block diagram (a) and corresponding equivalent circuit (b).

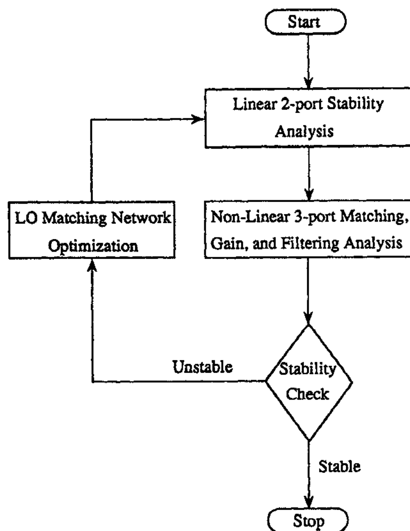


Fig. 2. Design steps flow chart.

ELEMENT	VALUE	ELEMENT	VALUE
L1	40 Ω, 0.07 λ	L12=L15	40 Ω, 0.02 λ
L2	60 Ω, 0.13 λ	L13=L16	40 Ω, 0.14 λ
L3	130 Ω, 0.02 λ	L14	40 Ω, 0.30 λ
L4	50 Ω, 0.25 λ	C1=C2	0.4 pF
L5	50 Ω, 0.02 λ	C3=C4	10.0 pF
L6	50 Ω, 0.08 λ	C5=C6=C7	4.0 pF
L7	50 Ω, 0.07 λ	C8=C9	0.1 pF
L8	40 Ω, 0.10 λ	SP1	N=7.5
L9	50 Ω, 0.18 λ		S=W=10 μm
L10=L17	50 Ω, 0.07 λ		Lin=300 μm
L11	50 Ω, 0.06 λ	SP2	SP1 + SP1

Fig. 3. Optimum value for each element in the matching networks and output filter.

A flow chart describing major steps in the design of the upconverter, for best operation with a 2.0 GHz IF signal and a 21.5 GHz LO signal, is shown in Fig. 2. Both small signal linear and large signal nonlinear parameters of a discrete 0.15μm $\times$ 200μm AlGaAs/InGaAs HJFET were applied in the circuit design. First, to investigate the stability of the mixer, the three-port network was reduced to a two-port network by replacing the LO source with a 50 Ω termination, and stability factor K and stability measure B1 were simulated for a sweeping drain current representing the effect of LO signal on FET transconductance modulation. At this step, unconditional stability of the upconverter was assured by optimizing the series transmission line $L4$ in the LO matching network. Then, the 50 Ω termination was removed, and a three-port nonlinear harmonic balance circuit analysis was carried out to optimize all matching networks as well as the output filter, for port-matching, conversion gain, and rejection of undesirable frequencies. Finally, the stability of the upconverter was again checked, and if necessary, the series transmission line $L4$ was reoptimized, and nonlinear analysis was repeated until all requirements were met. In the analysis, the gate was biased at the pinch-off voltage to realize the maximum mixing effect and minimum power consumption. Fig. 3 summarizes the optimum

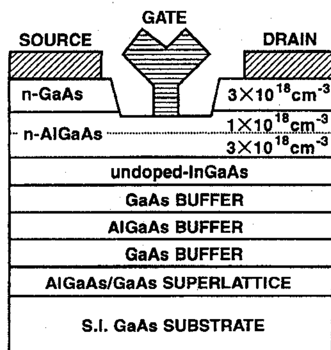


Fig. 4. Cross-sectional view for the step-doped AlGaAs/InGaAs HJFET.

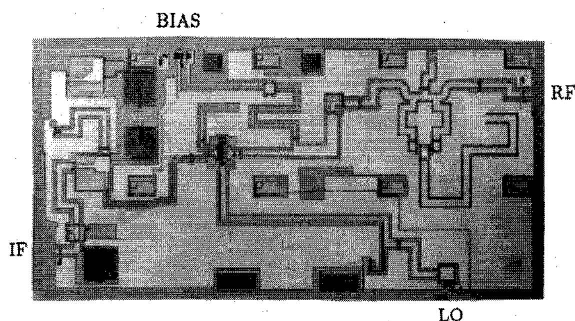


Fig. 5. K-band CPW upconverter MMIC chip. Chip size is 4 mm × 2 mm.

value for each element in the matching networks and output filter.

III. Fabrication Process and Device Characteristics

The K-band upconverter IC was fabricated on a 3-inch undoped SI GaAs substrate. A cross sectional view of an MOCVD step-doped AlGaAs/InGaAs HJFET used in the MMIC is shown in Fig. 4. The epitaxial layer structure consists of an AlGaAs/GaAs superlattice followed by GaAs and AlGaAs buffers, a 13 nm $In_{0.2}Ga_{0.8}As$ channel, a step-doped 40 nm 1×10^{18} cm^{-3}/3×10^{18} cm^{-3} $Al_{0.2}Ga_{0.8}As$, and an 80 nm 3×10^{18} cm^{-3} n^+-GaAs cap layer. In the FET fabrication process, mesa-isolation, conventional photolithography, electron beam evaporation and lift-off techniques have been employed. A CPW structure was used for transmission lines which permits chip size reduction and possibility of realizing transmission lines with different characteristics impedances without affecting the overall chip layout. To suppress odd modes, metal bridges were employed extensively to connect ground planes along the line particularly in the vicinity of a line discontinuity. An MIM structure was applied for fabricating resonant capacitors in IF matching network, dc blocking capacitors and bypass capacitors. Details of the fabrication process have been reported elsewhere [13], [14]. The HJFET used in the upconverter IC has a gate length of 0.15 μm and a total gate width of 200 μm (25 μm × 8 fingers). The device has a typical transconductance of 380 mS/mm and an f_T of 70 GHz both at a drain bias of 2 V with a reverse gate-drain breakdown voltage of 11 V, and a pinch-off voltage

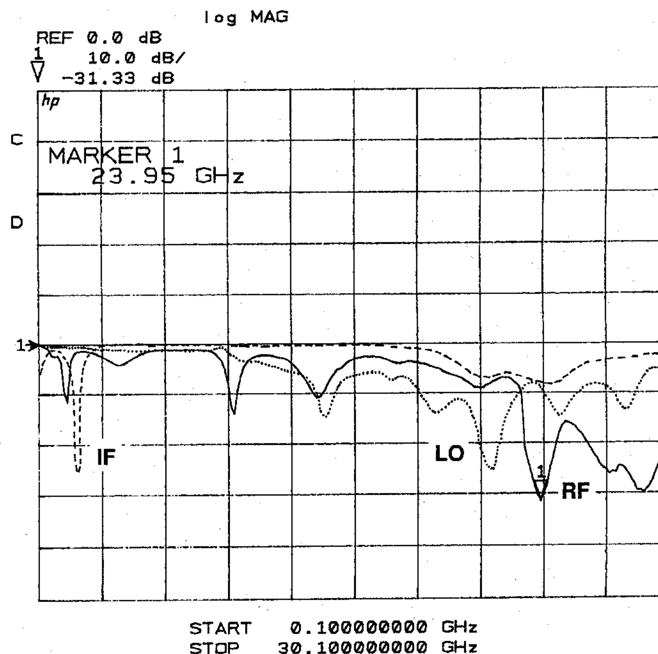


Fig. 6. Small signal matching characteristics for IF, LO, and RF ports.

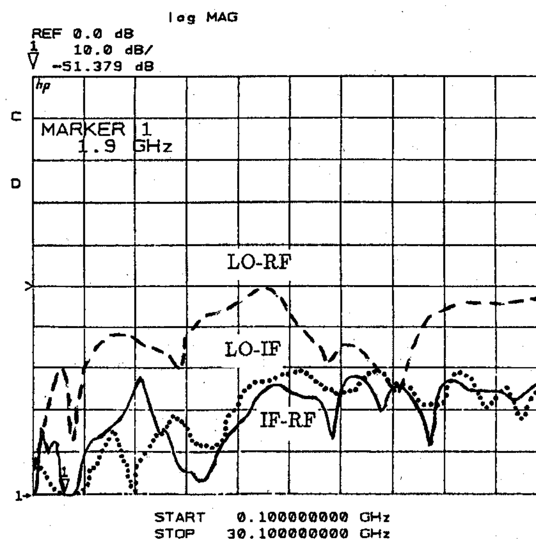
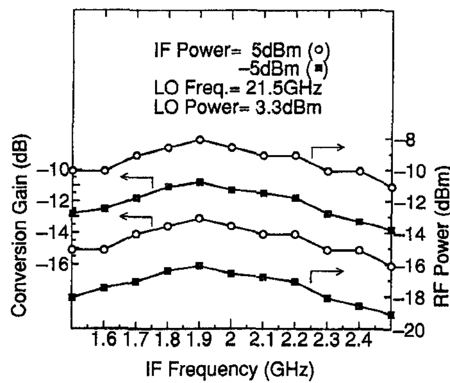


Fig. 7. Small signal LO-IF, LO-RF, and IF-RF port isolation.

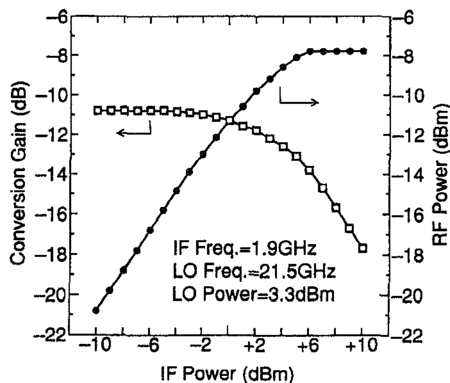
of −1.4 V. Measured minimum noise figure for the device is 1.1 dB at 24 GHz with an associated gain of 9.5 dB.

IV. Performance

Fig. 5 shows the chip photograph for the complete K-band CPW upconverter IC. Chip size is 4 mm × 2 mm. On-wafer Cascade Microtech probes were utilized to evaluate the chip performance. The FET gate bias was −1.4 V, corresponding to the pinch-off voltage, and the drain bias was 0.8 V. Fig. 6 shows small signal matching characteristics for the IF, LO, and RF ports. Measured in-band return loss for each port is better than 25 dB. Fig. 7 represents small signal LO to IF, LO to RF, and IF to RF port isolation for the upconverter. LO suppression at IF and RF ports is, respectively, better than 22

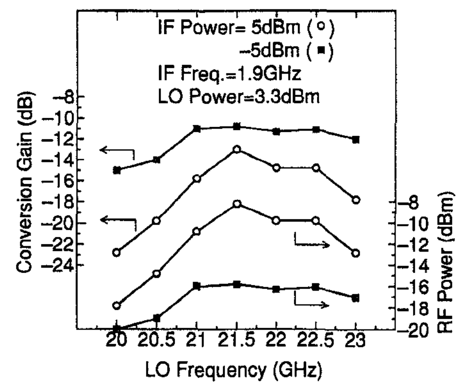


(a)

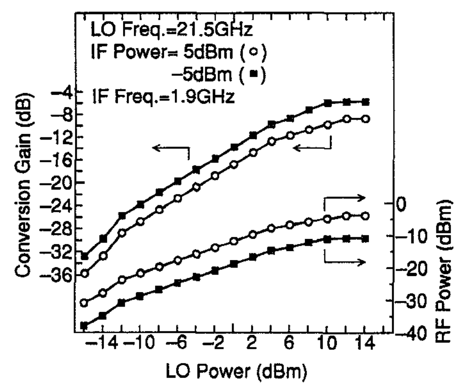


(b)

Fig. 8. Conversion gain and RF output power versus IF frequency (a) and power (b).



(a)



(b)

Fig. 9. Conversion gain and RF output power versus LO frequency (a) and power (b).

dB and 20 dB, and IF suppression at RF port is better than 35 dB. On the other hand, measured pass-band and rejection-band insertion loss for the output filter were, respectively, 3 dB and 18 dB, at an IF frequency of 2 GHz, and an LO frequency of 22 GHz. The filter, however, exhibited a graceful behavior change for an IF frequency in 1.5 to 2.5 GHz.

Large signal upconverter measurement results for the upper sideband frequency component are shown in Figs. 8 and 9. Fig. 8(a) depicts conversion gain as well as RF output power variation versus IF frequency for an LO power of 3.3 dBm, an LO frequency of 21.5 GHz, and IF power levels of −5 dBm and +5 dBm. Fig. 8(b) represents conversion gain and RF output power against IF power for an LO power of 3.3 dB, an LO frequency of 21.5 GHz and an IF frequency of 1.9 GHz. Conversion gain is constant for IF power levels lower than 2 dBm, and reduces with increasing IF power, for which RF output power saturates. Fig. 9(a) exhibits conversion gain as well as RF output power variation versus LO frequency for an LO power of 3.3 dBm, an IF frequency of 1.9 GHz, and IF power levels of −5 dBm and +5 dBm. Fig. 9(b) represents conversion gain and RF output power against LO power for an LO frequency of 21.5 GHz, an IF frequency of 1.9 GHz, and IF power levels of −5 dBm and +5 dBm. The upconverter operates with LO power levels as low as −10 dBm, and maximum conversion gain is −6 dB which is obtained for an IF power of −5 dBm and an LO power of 10 dBm. On the other hand, maximum output power is −3 dBm which is obtained for an IF power of 5 dBm and an LO power higher than 10 dBm. Both conversion gain and RF output power saturates for an LO power level higher than 10 dBm. A typical output spectra for the upconverter is depicted in Fig. 10. From the figure, suppression of the LO and LSB signals at the output port is, respectively, better than 18 dB and 16 dB. However, due to bandwidth limitation of the measurement system, the LSB signal spectrum is not displayed correctly.

No spurious oscillation was observed, and the upconverter was stable for an input IF signal in −10 to +10 dBm range, an input LO signal in −20 to +20 dBm range, and any gate voltage between 0 and −2 V. Experiments reported in this paper have been carried out at an ambient temperature. The upconverter performance is, however, anticipated not to be drastically affected by a change in the temperature, since the device is biased at the pinch-off voltage and the input LO power level is not remarkably high.

V. Conclusion

Design consideration and performance of a CPW upconverter MMIC for K-band wireless system applications were described. In the circuit design, the FET was treated as a three-port device in which the LO signal is applied to the source terminal. Including a 3 dB pass-band insertion loss of the filter, the upconverter exhibits a maximum conversion gain

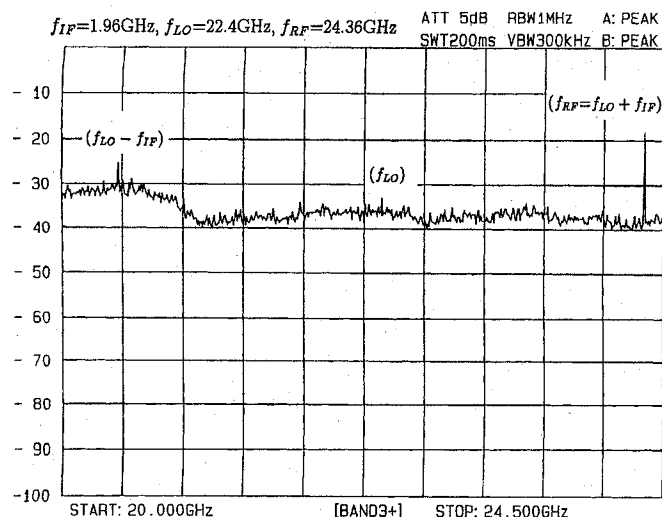


Fig. 10. A typical output spectra for the developed upconverter.

of −6 dB, and a maximum output power of −3 dBm. In the present paper, we described the "source injection" concept for the case of a K-band upconverter. The same design approach could be applied to realization of microwave/millimeter-wave downconverters, as well.

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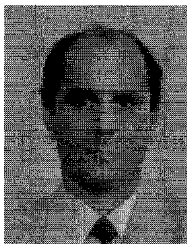

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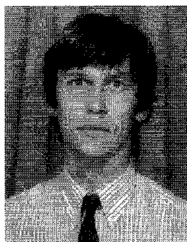

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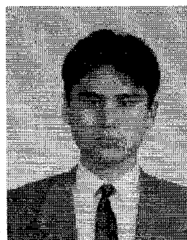

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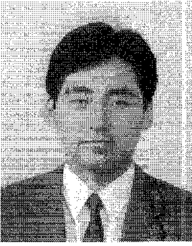

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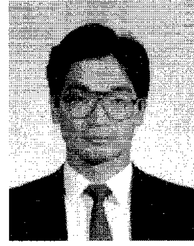

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