A Novel Monolithic HEMT-HBT Ka-band VCO-Mixer Design

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ABSTRACT

Here we present a novel demonstration of a HEMT-HBT VCO-Mixer which utilizes a unique active topology and is the first Ka-band MMIC demonstrated using GaAs HEMT-HBT IC technology. The MMIC integrates a novel HEMT-HBT cascode active mixer topology which operates similar to a dual-gate mixer. An all active HEMT-HBT VCO is constructed from the HBT of the cascode by providing a HEMT tunable active inductor-resonator. The VCO can be tuned from 28.5 to 29.3 GHz while providing $\approx$ 0 dBm of output power. Operated as an upconverter, the HEMT-HBT VCO-mixer achieves 6-9 dB conversion-loss over a 31 to 39 GHz output frequency band. The compact MMIC is 1.44 x 0.76 mm^2 in area due to the use of novel active circuit topologies and relies on minimal use of passive matching. The novel miniature active RF IC techniques demonstrated here have direct implications for future high complexity HEMT-HBT millimeter-wave MMICs.

Introduction

The ability to integrate HEMTs and HBTs on the same substrate can result in miniature MMICs which combine the best performance and circuit functions of each technology. For example, an earlier demonstration resulted in a compact 3x3 mm^2 S-band HEMT-HBT MMIC receiver which achieved a low DSB noise figure of 2.3 dB, LO-IF isolation > 40 dB, and 2-2 spur suppression $\approx$ 40 dBc by integrating a HEMT LNA with a double-balanced HBT Gilbert cell mixer[1]. Also, a unique circuit combination of HEMTs and HBTs have resulted in a low noise HEMT LNA which has been linearized using HBT active feedback, and resulted in as much as a 10 dB improvement in IP3 [2]. In this work, we further illustrate the functional versatility and performance advantage of monolithic HEMT-HBT circuit integration by demonstrating a unique Ka-band VCO-mixer which integrates a novel all-active VCO, a HEMT-HBT cascode mixer, and a high Q-factor HEMT active inductor/resonator.

HEMT-HBT Monolithic Integrated Circuit Techonology

The HEMT-HBT MMIC of this work was fabricated using a selective MBE IC technology. A cross section of the HEMT-HBT integrated device technology is illustrated in Fig. 1. This HEMT-HBT technology has previously been reported and described in detail [3]. The GaAs HEMT-HBT selective MBE technology integrates 0.2 µm gate-length pseudomorphic InGaAs-GaAs HEMTs and 2 µm emitter- width self-aligned base ohmic metal GaAs-AlGaAs HBTs.

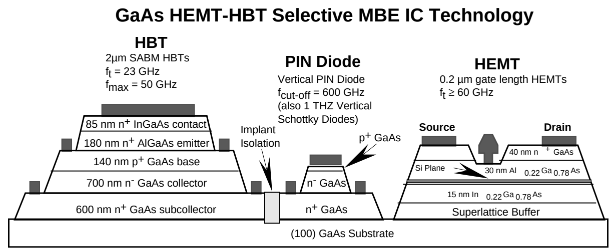

Fig. 1 Cross section of the monolithically integrated HEMT-HBT IC technology.

process, the 0.2µm HEMT devices achieve a G_m = 600 mS/mm, an f_T = 80 GHz, and a corresponding f_{max} = 150 GHz. The 2-µm HBT devices achieve a typical ß = 60 at a J_C=20 kA/cm^2, an f_T = 22 Ghz, and an f_{max} = 50 GHz. The HEMT and HBT devices grown by selective MBE and fabricated using the merged HEMT-HBT process exhibit dc and microwave performance equivalent to devices fabricated using conventional MBE and single-technology processes [3].

HEMT-HBT VCO-Mixer Design

Fig. 2 gives the detailed schematic of the novel HEMT-HBT VCO-mixer design. A HEMT-HBT cascode device configuration is used in order to obtain a low noise-high linearity mixer and operates similar to a dual-gate FET mixer where the gate and base inputs both modulate the cascode device's transconductance. Contrary to a conventional cascode topology, this HEMT-HBT cascode connection integrates a common-source (CS) HEMT with a common-collector (CC) HBT in order to accommodate a common-collector HBT VCO design. The mixer output is thus taken out of the emitter-drain node of the cascode connected devices which differs from conventional cascode applications. The gate of the CS HEMT is used as a low noise input while the base of the CC HBT transistor is used to construct a low phase noise tunable VCO. The gate of the CS HEMT device is passively matched over a 1-10 GHz RF input band. A unique HEMT-HBT VCO is constructed from the cascode's HBT by presenting a tunable high-Q HEMT active inductor-resonator in series with it's base. The VCO was designed for a center frequency of 30 GHz and is based on a previously reported all-HBT active VCO a design [4]. However, because of the limited frequency and Q-factor performance of the HBT active inductor, we employ HEMT

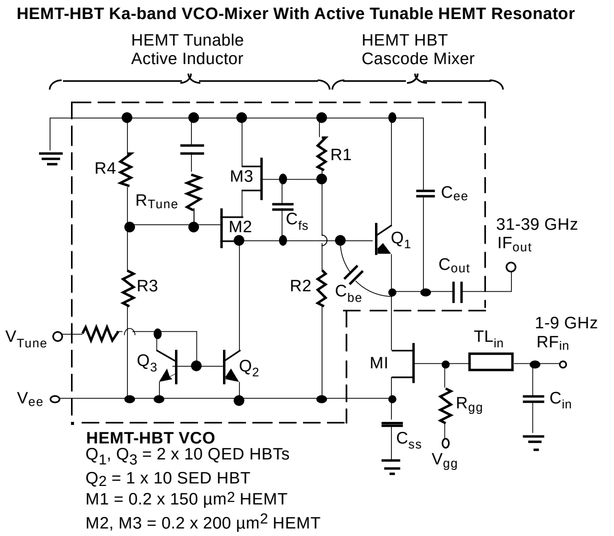

Fig. 2 Detailed Schematic of the novel HEMT-HBT VCO-mixer.

active inductor which is similar to the FET active inductor reported by Hara, et.al. [5].

Fig. 3 gives the broadband impedance characteristics of the HEMT active inductor including transmission line parasitics. This plot shows that there is a high and a low frequency region where the impedance looks inductive. At the higher frequency inductor band, the real impedance is also slightly negative. Because of the additional negative resistance provided by the active inductor at the higher frequency band, we utilize the inductance in this region to resonate with the base of the CC HBT transistor which comprises the cascode.

Fig. 4 gives the simulation of the oscillator start-up condition of the HEMT-HBT VCO-mixer. The frequency of oscillation occurs where the imaginary part of the total oscillator + active inductor impedance crosses zero with a positive reactive slope, given that the real part of the total impedance is negative. This simulation which includes layout parasitics indicates a nominal oscillation frequency of about 29.5 Ghz.

Using the 30 GHz active tunable HEMT-HBT VCO, a 1-9 GHz signal presented at the HEMT low noise RF input port can be unconverted to a 31-39 GHz IF output band. The VCO frequency can be bias tuned through V_{tune}, which can be used to adjust the HEMT active inductance by changing the HEMT bias current and respective transconductance. An increase in V_{tune} will increase I_{ds} and the HEMT G_m which will consequently reduce the effective inductance. This in turn will increase the frequency of resonance and oscillation.

Fig. 5 shows a microphotograph of the HEMT-HBT VCO-mixer. The compact MMIC is only 1.44x0.76 mm^2 and is self-biased through a -6V supply while consuming 40 mA. The MMIC integrates 3 HEMTs and 3 HBT devices using the selective MBE IC technology [3]. With the exception of the simple L-C network used to match the CS HEMT RF input, the design consists of an all active circuit topology including the tunable VCO resonator.

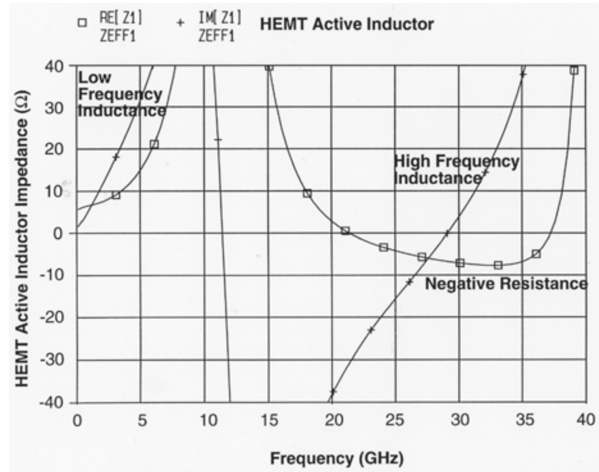

Fig. 3 Broadband impedance characeristics of the HEMT active inductor.

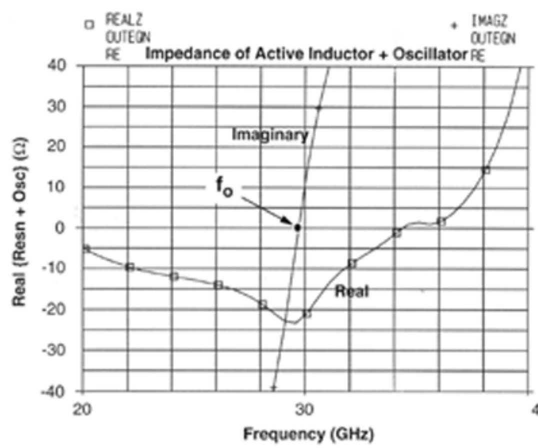

Fig. 4 Simulation of the oscillator start-up condition of the HEMT-HBT VCO-mixer.

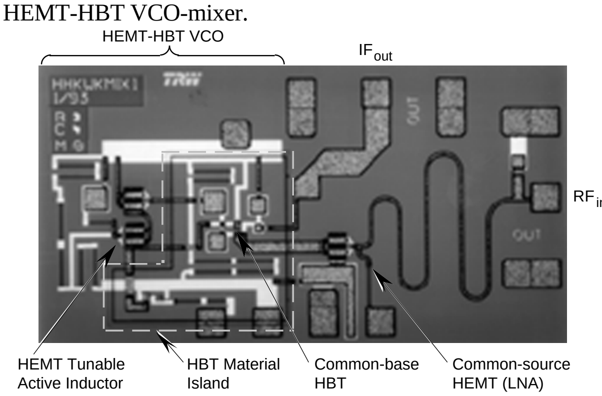

Fig. 5 Microphotograph of the HEMT-HBT VCO-mixer. The Compact MMIC is only 1.44x0.76 mm^2

Measured Results

The HEMT-HBT cascode was employed as an active mixer because it combines the best DC and RF properties of both HEMTs and HBTs into a single device and can potentially result in improved active mixer linearity and noise characteristics. Fig. 6a) gives the I-V characteristics of the HEMT-HBT cascode device which

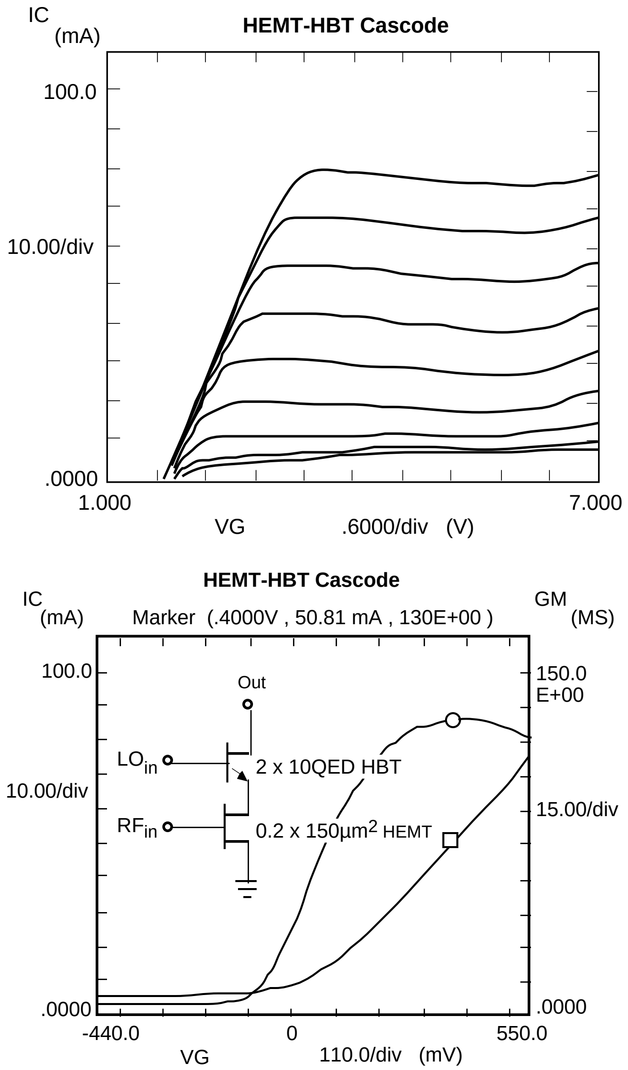

Fig. 6 HEMT-HBT cascode dc performance:
a) I-V and, b) transconductance characteristics.

qualitatively illustrates the superior output resistance and breakdown voltage compared to a single HEMT device alone. The HBT helps provide higher output impedance as well as more abrupt I-V knee characteristics which are known to be conducive of higher linearity in RF circuits. The high output impedance can be advantageous for inhibiting VCO AM-to-PM noise induced from the power supply while the linear HEMT-HBT cascode characteristics should improve the spurious free operation of the VCO-mixer. Fig. 6b) also gives the G_m and I_{ds} vs. V_{gs} of the cascode device. The cascode achieves a higher normalized G_m of 850 mS/mm compared to ≈ 500-600 mS/mm for the conventional CS HEMT device and is due to the higher dc output resistance provided by the HBT. Although the dc characteristics of the HEMT-HBT cascode may not explicitly be indicative of better VCO or mixer performance in our unique design configuration, it does demonstrate some advantageous device characteristics which could not otherwise be realized by either HEMT or HBT alone.

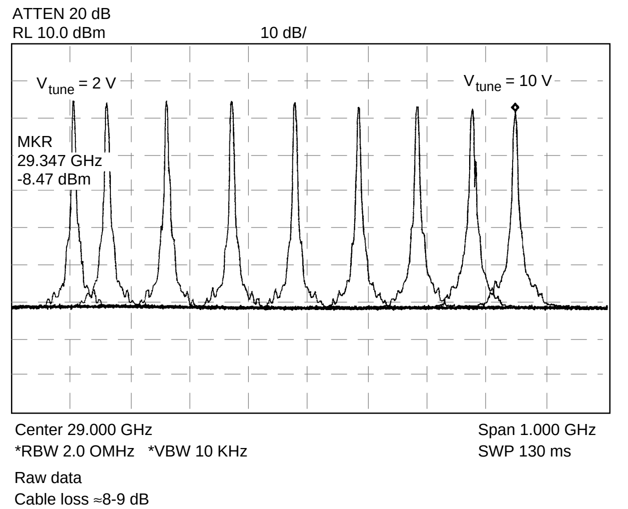

Fig. 7 Measured (uncallibrated) HEMT-HBT VCO tuning spectrum for tuning voltages between 2V and 10V.

The tuning performance of the HEMT-HBT VCO is illustrated in Fig. 7 which gives the measured VCO output spectrum at the IF port of the VCO-mixer with NO RF input signal applied. The measurement does not include cable and probe loss of ≈ 8 dB. By adjusting the V_{tune} bias of the HEMTactive inductor-resonator from 2-10V, the frequency is increased by as much as 3 % as illustrated in Fig. 7. This is due to the reduction in the HEMT active inductance as the bias current and corresponding HEMT G_m's are increased. Fig. 8 gives the calibrated VCO tuning characteristics which illustrate a frequency tuning range from 28.5 to 29.3 GHz while achieving a flat output power of ≈ 0 dBm. This is the first millimeter-wave performance achieved using an all active HEMT-HBT VCO topology.

Millimeter-wave frequency conversion performance was also achieved from the integrated HEMT-HBT VCO-mixer MMIC which demonstrated Ka-band upconversion operation. Fig. 9 shows the conversion-gain and RF-IF isolation across a 31-39 GHz IF output for a swept RF input from 2-10 GHz @ -20 dBm power. The conversion loss is between 6-9 dB across the band with an RF-IF isolation > 13 dB. In this measurement, the IF output is lightly coupled out of the emitter/drain node connection of the cascode without any impedance matching. Higher conversion gain can be obtained by employing a matched IF buffer amplifier at this upconverted IF output.

Fig. 10 shows the upconverted IF output spectrum (not calibrated) for a fixed RF input at 5 GHz and -20 dBm power. The IF spectrum illustrates the predominant 29.25 GHz LO signal along with the upconverted LSB and USB IF signals. The spectrally clean output is indicative of proper mixing performance obtained by the novel HEMT-HBT cascode mixer.

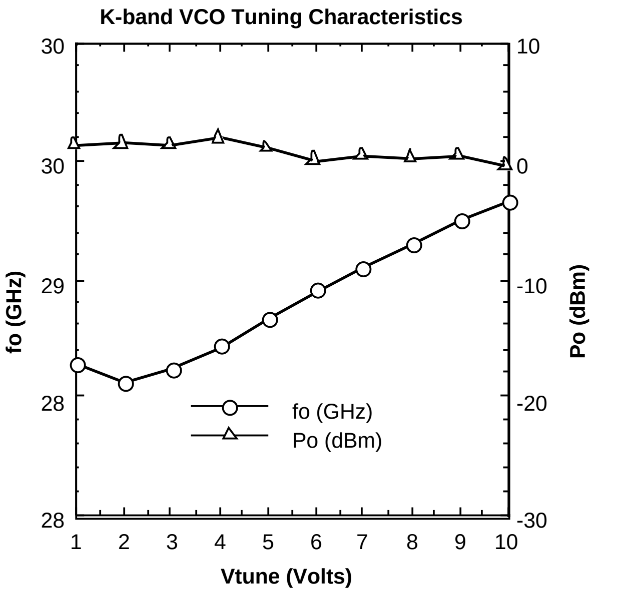

Fig. 8 Measured (calibrated) HEMT-HBT VCO frequency tuning and output power characteristics.

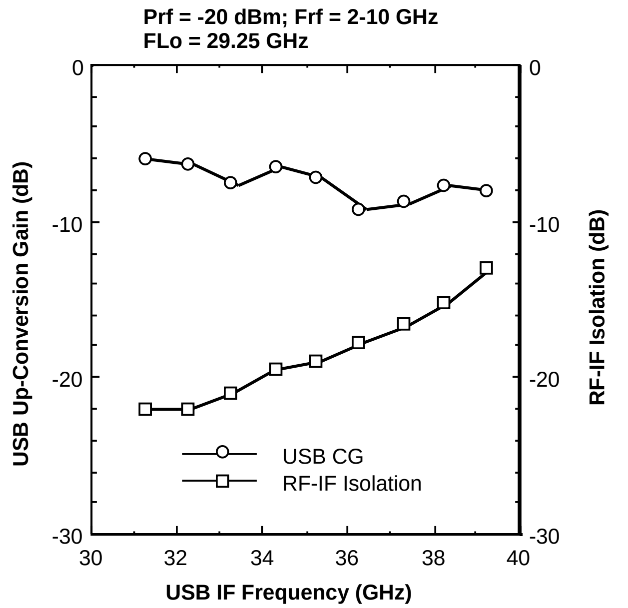

Fig. 9 Measured conversion-loss and RF-IF isolation across a 31-39 GHz IF output for a swept RF input from 2-10 GHz at -20 dBm power.

Conclusion

A novel Ka-band HEMT-HBT VCO-mixer MMIC has been demonstrated using selective MBE technology.
The design integrates a novel HEMT- design integrates a novel HEMT- HBT cascode mixer with a HEMT tunable active inductor-resonator which is used to construct a VCO with the HBT device of the cascode. Compact size and Ka-band VCO and mixer performance were demonstrated with this all-active topology. The unique design topology can be used as an alternative to the lower Q multi- vibrator circuits typically found in clock-recovery and PLL
circuit applications and demonstrates the design versatility of the HEMT-HBT integration technology which can produce miniature monolithic millimeter-wave IC solutions using compact analog design techniques.

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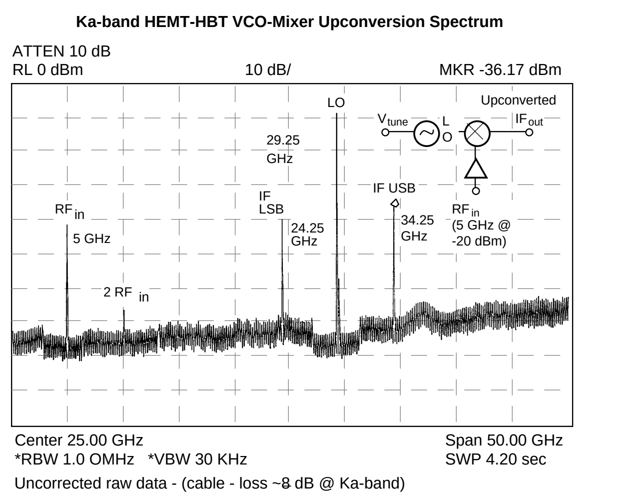

Fig. 10 Upconverted IF output spectrum (not calibrated) for a fixed RF input at 5 GHz and -20 dBm power.

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