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A Ka-band monolithic low phase noise coplanar waveguide oscillator using InAlAs/InGaAs HBT ☆

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Abstract

A Ka-band oscillator has been designed, fabricated and tested using InAlAs/InGaAs HBTs. Coplanar waveguide technology has been employed to improve the *Q*-factor of the circuit. An output power of 2.6 dBm with DC to RF conversion efficiency of 7.8% was measured at 31.7 GHz. Low phase noise of −87 and −112 dBc/Hz were achieved at an offset frequency of 100 kHz and 1 MHz respectively. These low phase noise values can be attributed to the low $1/f$ noise of the InAlAs/InGaAs HBT devices and the coplanar design used for the circuit.

Keywords: InAlAs/InGaAs; HBT; Oscillator; Phase noise

1. Introduction

InP-based HBT technology is attractive for millimeter wave frequency signal generation such as remote sensing and advanced imaging applications due to the low $1/f$ device noise. Low phase noise InP-based HBT VCO circuits have been reported at 30, 77 and 94 GHz using microstrip design which involves wafer thinning and backside via holes [1–3]. Coplanar waveguides, on the other hand, provide simplicity in processing but require more recently developed simulation tools. Coplanar waveguide designs are also attractive for reducing losses associated with circuits made using this technology.

A coplanar waveguide InAlAs/InGaAs HBT Ku-band VCO has been reported with 18 GHz oscillation frequency. It achieved a phase noise of −72 and −96 dBc/Hz at 100 kHz and 1 MHz offset frequency from the carrier [4]. Several other coplanar waveguide HBT oscillators have also been reported. A 15 GHz AlGaAs/GaAs-based coplanar HBT VCO was reported with −85 and −110 dBc/Hz phase noise at 100 kHz and 1 MHz offset respectively [5]. SiGe-based HBT coplanar oscillators were also reported at 26 and 38 GHz with 55 dBc/Hz at 100 kHz offset [6,7].

In this work, we report a further advancement in InP-based HBT MMIC technology by combining high performance InAlAs/InGaAs HBTs with coplanar waveguide technology to demonstrate higher than previously reported frequency of operation at Ka-band, which was accompanied by excellent phase noise characteristics. An oscillation output power of 2.6 dBm with a DC to RF conversion efficiency of 7.9% was achieved at 31.7 GHz and low phase noise of −87 and −112 dBc/Hz were measured at 100 kHz and 1 MHz offset from the carrier frequency.

2. HBT process and characteristics

The InAlAs/InGaAs HBT structure used for oscillator realization was grown by MBE at TRW. It consists

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of a 4300 A sub-collector, a 7000 A collector, an 800 A beryllium-doped base, a graded InAlGaAs transition layer, InAlAs emitter layers and InGaAs emitter cap layer. A graded InAlGaAs layer was used to reduce the turn-on voltage by eliminating the emitter–base conduction band spike. A thick, low doped collector was employed to increase the breakdown voltage.

The MMIC circuits were designed, fabricated and tested at the University of Michigan. Key features of the technology include a self-aligned base and a lateral-undercut collector. An all wet etch-based process was employed to create the mesa and trench. Spiral inductors and MIM capacitors were incorporated for matching and bypass circuits. Ni/Cr thin film resistors were also deposited with a sheet resistance of 20 Ω/□.

The Gummel plot of a $5 \times 10\ \mu m^2$ InAlAs/InGaAs HBT is shown in Fig. 1. Detailed DC and microwave characteristics of the employed HBTs are described in a previous report [8]. A low offset voltage (~0.15 V) and relatively high (~8.5 V) breakdown voltage were measured for these HBTs.

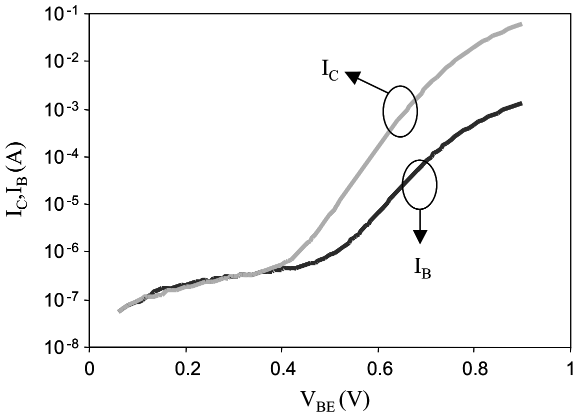


Fig. 1. Gummel plot of a $5 \times 10\ \mu m^2$ InAlAs/InGaAs HBT.

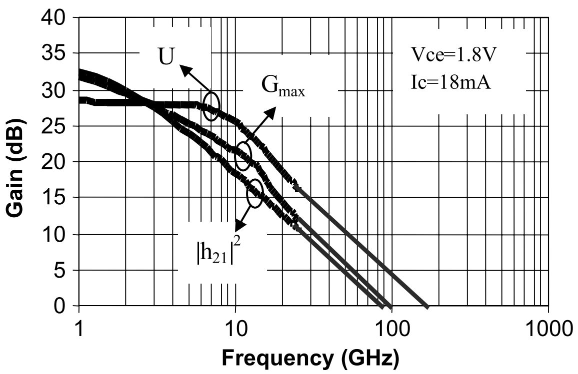


Fig. 2. Microwave characteristics of a $5 \times 10\ \mu m^2$ InAlAs/InGaAs HBT.

Fig. 2 shows the microwave characteristics of a $5 \times 10\ \mu m^2$ HBT. As can be seen, a 90 GHz f_T and 150 GHz f_{max} were achieved despite the thick and low doped collector design. The self-aligned base and lateral undercut of the collector helped in reducing the parasitics, such as R_b and C_{BC}, and led to the reported performance.

3. HBT modeling

The small-signal HBT equivalent circuit model used in this work is based on the T-topology reported by the authors [9] and is shown in Fig. 3(a). It is derived using an analytical modeling procedure, which accounts for the physical structure and layout of the device. The approach not only allows high accuracy HBT modeling but also presents physical insight into the performance-limiting aspects of the devices. The equivalent circuit element values at the bias used for oscillation ($V_{CE} = 1.80$ V, $I_C = 16$ mA) are tabulated and presented in Fig. 3(b).

As can be seen, equivalent circuit elements are represented by extrinsic and intrinsic components to account for the geometry dependence of the HBTs. The base–emitter capacitance is divided into the junction capacitance C_{BE} and diffusion capacitance C_D. The pad capacitance and other parasitic capacitance introduced by the physical layout are also included in the model.

Computer optimization tools and fitting were employed to complete the above described analytical modeling. A standard "multi-bias technique" was developed and used in this work to extract the small-signal circuit model under various bias conditions. Details of this procedure can be found in Ref. [10].

4. Oscillator design and simulation

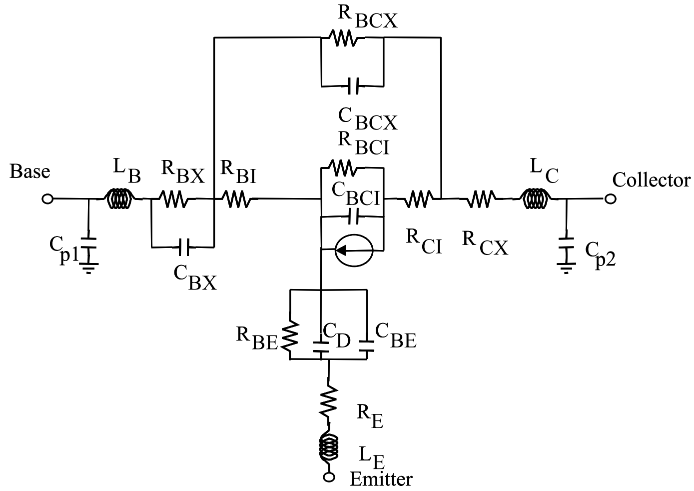
Design and simulation of the MMIC oscillators was done using the commercially available tool "Libra". For coplanar waveguide discontinuities and junctions, equivalent circuit models have been built through 3D full-wave analysis using "Momentum".

The oscillator design consisted of ensuring that the following conditions are satisfied.

$$\begin{aligned} &\mathrm{Re}(Z_{osc} + Z_{load}) < 0 \\ &\mathrm{Im}(Z_{osc} + Z_{load}) = 0 \\ &\frac{\partial(\mathrm{Im}(Z_{osc} + Z_{load}))}{\partial\omega} > 0 \end{aligned} \tag{1}$$

Fig. 4 shows the simulation results for the Ka-band MMIC HBT oscillator. As can be seen, the oscillation conditions indicated in Eq. (1) are satisfied.

(a)



(b)

C_{p1}=0.0165pF	L_B=0.0315nH	R_{BI}=5.86Ω	R_{BX}=0.50Ω	R_{BCX}=77.236KΩ	C_{BCX}=0.004pF
R_{BCI}=193KΩ	C_{BCI}=0.0014pF	R_{BE}=2.03Ω	C_D=0.27pF	C_{BE}=0.42pF	R_E=2.67Ω
L_E=0.0250nH	R_{CI}=0.1286Ω	R_{CX}=0.75Ω	L_C=0.035nH	C_{p2}=0.0165nH	

Fig. 3. (a) Small-signal circuit model for InAlAs/InGaAs HBT, (b) typical small signal equivalent circuit model parameters for a 5×10 μm² InAlAs/InGaAs HBT ($V_{CE} = 1.4$ V, $I_C = 12$ mA).

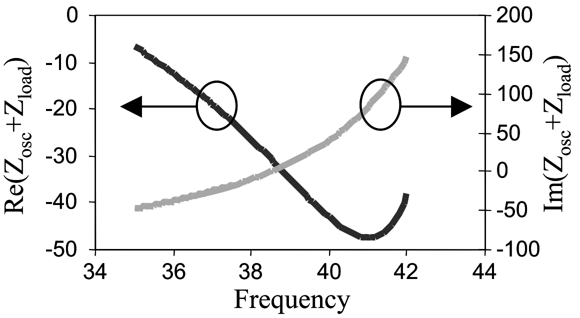


Fig. 4. Simulation results for the InP HBT Ka-band oscillator ($V_{CE} = 1.4$ V, $I_C = 12$ mA).

A 2×30 μm² HBT was used for active device. The VCO design employed HBT in common-base topology with the base connected to ground. By using air-bridge technology, one side of the emitter finger was connected to an open stub while the other side was used for biasing. The length of the coplanar line was optimized to present the maximum negative resistance at the collector port. An output-matching network was designed to match the load impedance to 50 Ω. The circuit photograph of the Ka-band coplanar waveguide InAlAs/InGaAs HBT oscillator is shown in Fig. 5. The size of the VCO chip was 1.58×2.58 mm².

5. Measurements results and discussion

The performance of the oscillator was tested on wafer using a spectrum analyzer. Fig. 6 shows the variation of output power and oscillation frequency as a function of emitter current. The collector voltage was fixed to be 0.9 V while the base–emitter voltage was increased from 0.69 to 0.89 V. As can be seen, the oscillation frequency varied with bias from 31.6 to 32.7 GHz.

By increasing the collector–emitter voltage, the output power of the oscillator could be increased further. Fig. 7 illustrates the oscillation frequency and output power as a function of collector–emitter voltage with emitter current of 12 mA. As can be seen, with emitter current of 12 mA and collector–emitter voltage of 1.93 V, the output power achieved was 2.6 dBm with 7.9% DC to RF conversion efficiency at an oscillation frequency of 31.695 GHz.

The DC to RF conversion efficiency increased as the emitter current was decreased due to the smaller DC bias, which was not accompanied by considerable lowering of negative resistance. For example, at emitter current of 6 mA and collector–emitter voltage of 1.63 V, the output power obtained at 32.75 GHz was 0.6 dBm, corresponding to a DC to RF conversion efficiency of 11.7%.

Fig. 8 shows the power spectrum of the oscillator. The oscillation frequency is in this case 31.695 GHz. The

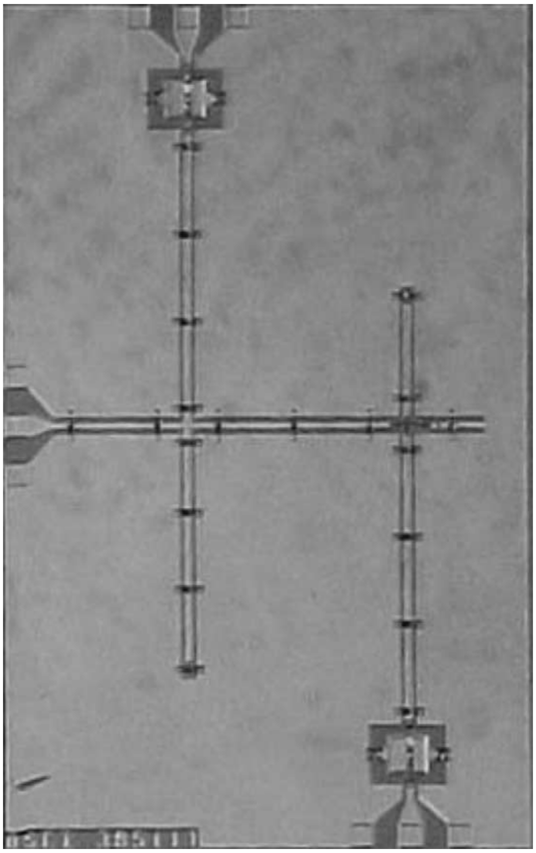


Fig. 5. Photograph of Ka-band InAlAs/InGaAs coplanar waveguide oscillator (1.58 × 2.58 mm^2).

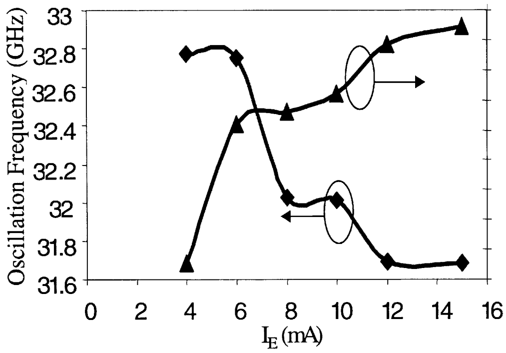


Fig. 6. Oscillation frequency and output power as a function of emitter current.

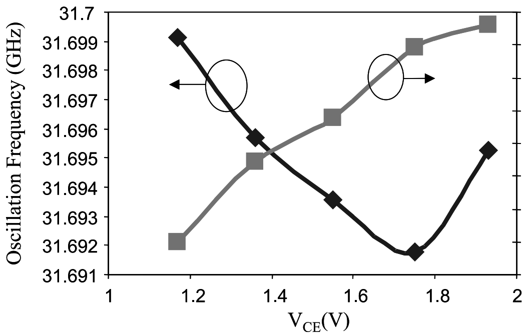


Fig. 7. Oscillation frequency and output power as a function of collector voltage.

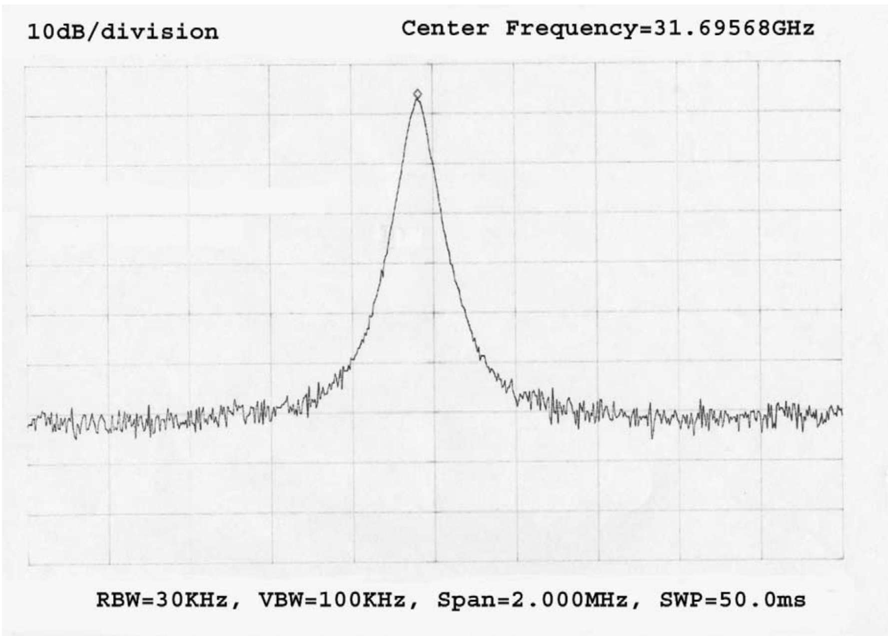


Fig. 8. Oscillation spectrum of the coplanar InAlAs/InGaAs HBT oscillator (V_{CC} = 1.4 V, I_C = 12 mA).

phase noise achieved for this oscillator was low as evidenced by the measured values of −87 and −112 dBc/Hz at an offset frequency of 100 kHz and 1 MHz from the center frequency respectively. $1/f$ noise characterization of the InAlAs/InGaAs HBTs used for oscillator design in this work showed that for a device biased at 1 and 10 mA, $1/f$ noise is of the order of 1×10^{-18} and 1×10^{-15} A^2/Hz at 10 Hz respectively. Thus, the measured low phase noise of the designed Ka-band oscillator can be attributed to the employed coplanar technology for improving the quality factor of the circuit and the low $1/f$ device noise of InAlAs/InGaAs HBTs.

6. Conclusion

A Ka-band oscillator was designed and fabricated using InAlAs/InGaAs HBT technology. Coplanar waveguide technology has been employed to improve the Q-factor of the transmission line resonator and hence its phase noise. The measured oscillation frequency was about 31.7 GHz and an output power of 2.6 dBm with 7.8% DC to RF conversion efficiency were obtained. Low phase noise of −87 and −112 dBc/Hz have been achieved at an offset frequency of 100 kHz and 1 MHz respectively. This low phase noise is attributed to the low $1/f$ noise of the InAlAs/InGaAs HBT technology combined with coplanar technology used for oscillator implementation.

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