Low Phase-Noise Monolithic GaInP/GaAs-HBT VCO for 77 GHz

F. Lenk, M. Schott, J. Hilsenbeck, J. Würfl, and W. Heinrich

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), D-12489 Berlin, Germany

Abstract — **Coplanar W-band push-push VCO MMICs using GaInP/GaAs HBTs are presented. One circuit operates at 77 GHz with phase noise of –92 dBc/Hz at 1 MHz offset. To our knowledge this is the first fully monolithic W-band VCO with phase noise better than -90 dBc/Hz. A second version with two varactor diodes yields an almost threefold relative tuning bandwidth.**

I. Introduction

Low phase-noise VCOs are key building blocks in mm-wave systems for wireless communications and sensors. For W-band applications, several VCO approaches were presented [1]-[2], most of them using GaAs HEMTs because to their high transit frequency. But HEMTs generate a high level of 1/f noise. Hence, only systems with external resonator or injection locking [3] achieve acceptable phase noise.

Because of the vertical current flow, the HBT offers superior 1/f-noise performance. Up to now, Si- or SiGe-based HBTs cannot address W-band frequencies. Therefore, InP or GaAs HBT technology is preferred [4]-[5], which combines high frequency potential with low 1/f-noise. As is shown in the following, GaInP/GaAs-based MMICs can achieve reasonable output power at 77 GHz combined with phase-noise levels below –90 dBc at 1 MHz offset.

The circuits presented rely on the push-push principle. Since no combiner is used, the second harmonic is extracted directly at the virtual ground as shown in [2] and [6]. In contrast to many other push-push oscillators, the fundamental frequency is terminated reactively, which increases quality factor Q_L. To reject even-mode oscillation, a second combining point is introduced.

II. Push-Push Principle

In a differential oscillator, two symmetric oscillator circuits are combined into one. Depending on the connection point, the two oscillators run in-phase or anti-phase. In a push-push oscillator, a ground node of the single stage is used as connection point. Since signals are in anti-phase, it acts as virtual ground. At this node, the fundamental cancels out, but the second harmonic interferes constructively and is extracted. This concept has several advantages. The frequency range of the active device is extended, because the devices are operating at one half of the desired output frequency. This results in higher gain and lower phase noise. In some cases, higher Q-values can be obtained at the lower frequency as well.

Moreover, since the output node forms a virtual ground at the fundamental frequency, impedance termination is facilitated. Any load can be connected to the output. It will only affect the second and further even harmonics but not the fundamental. Thus, a complex output matching network can be avoided.

III. Technology

Metalorganic Vapor-Phase Epitaxy (MOVPE) is used for growing the epitaxial layers. For further details see [7]. The HBT MMICs are fabricated on an in-house industry-compatible 4" process line with stepper lithography. The process comprises 14 mask levels.

To achieve low 1/f-noise and high f_{max}, the emitter-base mesa fabrication step has to be designed very carefully: with smaller under-etching of the emitter metal, which is used as an etch mask, the distance from emitter to base metalization decreases. This yields lower base resistance R_b and thus higher f_{max}. In the same way, the cross-section area of the emitter increases and hence emitter resistance and 1/f-noise decrease. To achieve small under-etching an interferometrically controlled double dry-etch process was developed using both anisotropic and isotropic etching: In a first step, approx. 120 nm of the InGaAs/GaAs emitter contact layer are etched anisotropically, in the subsequent step the remaining GaAs is etched isotropically using the GaInP-emitter as etch-stop layer.

Ledge technology is used to eliminate emitter-base surface-leakage and thus excessive 1/f-noise. He^+-implantation is applied for device-isolation. In order to reduce the base-collector capacitance C_{bc} ($C_{bc} = C_{bc,intr} + C_{ex}$), we introduce an additional He^+-implantation in the outer region of the base fingers. As a result, the underlying base layer and the upper part of the collector (approx. 800 nm) become insulating, which strongly decreases C_{ex}. Together with a reduction of the base-emitter distance from 1.3 µm to 0.5 µm, this increased f_{max} from 95 GHz to 170 GHz.

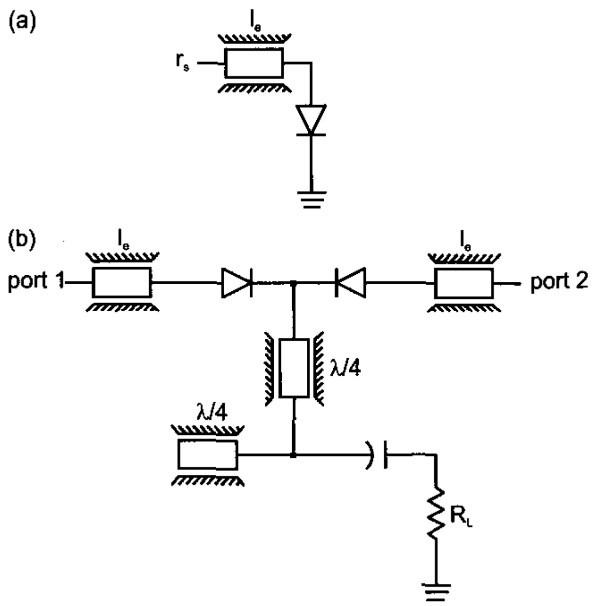

Fig. 1. Emitter wiring with varactor-loaded CPW for single-stage VCO (a) and combining circuit for push-push oscillator (b).

The coplanar MMIC process is complemented by MIM-capacitors (dielectric material: SiN_x), thin-film-resistors (NiCr), spiral inductors, and air bridges (electroplated gold).

IV. CIRCUIT DESIGN

The oscillators are designed according to common feedback theory. Shifted short stubs at base and collector yield a negative resistance at the emitter port. As illustrated by Fig. 1 (a), the length l_e of a varactor-loaded CPW is used to adjust the phase of the single-stage reflection factor r_s in order to fulfill the oscillation condition.

The ground node of the varactor is chosen as combining node for the push-push design (see Fig. 1 (b)). As mentioned in Sec. II, a load at this node will not affect the fundamental frequency in the odd mode, but it is important for odd- and even-mode separation. Simulating the combining circuit shown in Fig. 1 (b) one finds for odd- and even-mode reflection r_{odd} and r_{even}, respectively:

$$r_{odd} = S_{11} - S_{12} \qquad r_{even} = S_{11} + S_{12} \qquad (1)$$

Connecting ground directly to the combining point, the two oscillators separate completely and so there would be no phase relation between them any more. S_{12} equals zero in this case and from (1) one obtains identical odd- and even-mode reflection. On the other hand, using a high impedance for the load maximizes S_{12} and therefore the separation between the two modes.

For all cases, the odd-mode reflection r_{odd} is equal to single-stage reflection r_s, independent of the loading, because of the virtual ground in the combining node. In order to achieve a good suppression for the even-mode, we choose the output circuit as shown in Fig. 1 (b). For the fundamental at 38 GHz, the λ/4 open stub short-circuits the load impedance R_L. With the second λ/4 CPW section, this short behaves like an open in the combining point and a good separation between odd and even mode is obtained.

For the second harmonic at 77 GHz, the length of the open stub is λ/2. Therefore, it represents an open at the input as well and the combining point is loaded with R_L, which equals 50 Ω. With this configuration, a good matching for the second harmonic is obtained without any further network elements.

Finally, one has to check for a possible out-of-band even-mode operation. This is suppressed by a second combining node at the base of the transistors. Again a λ/4 stub is used to get a good mode separation.

The second VCO version is based on the same circuit principle. However, the ground-to-ground spacing of the CPWs is scaled up by a factor of 3 to increase the quality factor. Loading the base with a second varactor with separate tuning input leads to a higher VCO bandwidth.

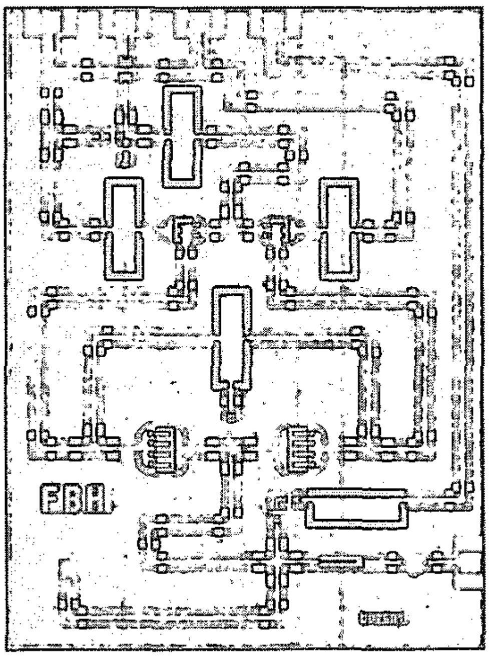

Fig. 2 Chip photo of the 77 GHz VCO (version (i), chip size is 1.3 x 1.7 mm^2).

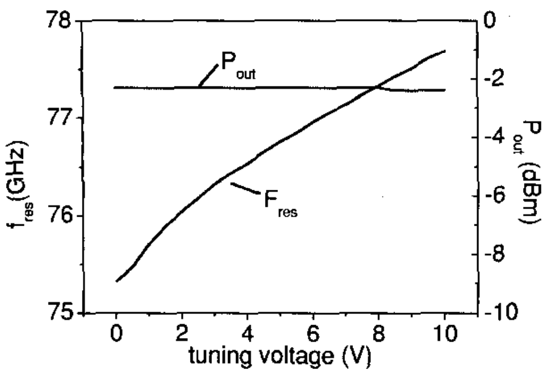

Fig. 3 Tuning characteristic of the VCO version (i): output power and oscillation frequency as a function of tuning voltage.

V. RESULTS

Fig. 2 presents a chip photo of the first VCO version. For test purposes, one can probe all bias feeds separately by removing airbridges. Otherwise, only collector and tuning voltage need to be connected. In parallel to the output branch, a large resistor is used to feed the varactor tuning voltage.

Because the push-push principle is used with second harmonic extraction in the combining node, the output circuit has only a very weak influence on the fundamental. Therefore, load-pulling effects remain small. For further load-pull rejection, a 10 dB attenuator is integrated on the chip. As can be seen from Fig. 3, there are no steps or spikes in the tuning characteristic indicating load-pulling phenomena.

The power was measured using a HP W8486A power sensor. In contrast to spectrum analyzer measurements this leads to an almost constant output power of

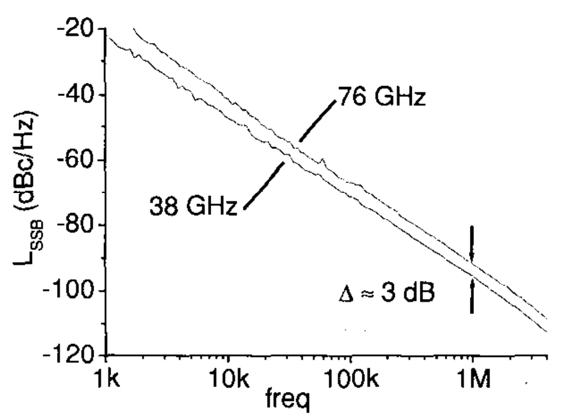

Fig. 4 SSB phase noise against offset frequency (VCO version (i)).

$P_{out} = -2.3$ dBm. Using the circuit in a system, the 10 dB on-chip attenuator can be omitted and an output power of 7.7 dBm is available.

Because the varactor is biased against the 5 Ω emitter resistor, for low tuning voltages (< 1 V) some non-linearity in the tuning curve must be accepted. The measured frequency range is $f_{res} = 76.5 \pm 1.2$ GHz, corresponding to 3.1 % tuning bandwidth.

Phase noise measurements were performed with the E5504 system from Agilent. First, the signal was mixed down to the lower GHz range and then measured applying the delay-line method. The results are shown in Fig. 4. For the 77 GHz signal, a phase noise of -92 dBc/Hz was measured at 1 MHz offset frequency. Collector voltage and current were 4.5 V and 108 mA, respectively.

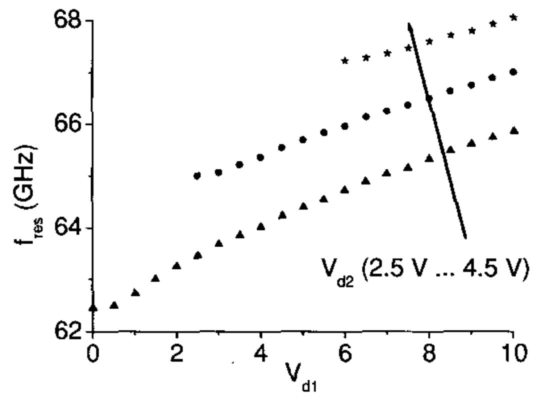

Fig. 5 Frequency tuning of the VCO version (ii): oscillation frequency against tuning voltage at varactor 1 with the voltage at varactor 2 as a parameter.

At the same port, the fundamental was measured. The rejection is better than 25 dB. Phase noise at the fundamental is approximately 3 dB below the value at the second harmonic (see Fig. 4). This means one has only a 3 dB degradation from first to second harmonic while 6 dB difference are obtained when using a frequency doubler. This is a further advantage of the push-push concept.

The second VCO was realized with CPW of larger cross-sectional dimensions. Due to model inaccuracies for structures of this size, the frequency missed the target value by 14 %. The oscillator has an additional varactor at the base. Therefore, two tuning voltages can be applied. The frequency tuning characteristics are plotted in Fig. 5, where V_{d1} and V_{d2} denote the voltages at emitter and base varactor, respectively. With V_{d2} a coarse adjustment of the frequency is done. 5.6 GHz tuning range are measured, which refers to 8.6 % of the center frequency of 65.3 GHz.

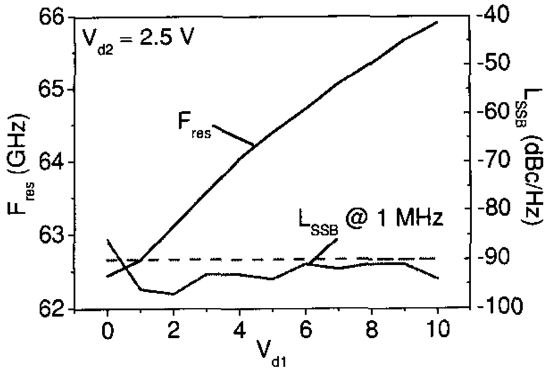

Fig. 6 Tuning characteristics of the VCO version (ii): frequency and phase noise (spectrum analyzer measurements) as a function of tuning voltage.

For $V_{d2} = 2.5$ V, phase noise was measured using a spectrum analyzer. Fig. 6 presents the results. At optimum, a phase noise improvement of 5 dBc/Hz is achieved over first VCO version. Because of the larger CPWs and the additional varactor the chip size enlarges by a factor of 2 to the first VCO. Output power of this circuit is about -20 dBm.

VI. Conclusions

Two fully monolithic push-push oscillator MMICs are presented. The first version operates in the 77 GHz band with an output power of –2 dBm (8 dBm accounting for the on-chip isolation element), a tuning bandwidth of 3 % and a phase noise better than -90 dBc/Hz, measured at 1 MHz offset frequency. To our knowledge, this is the best phase noise of a fully on-chip VCO in this frequency range (see Fig. 7). The second oscillator version uses larger CPWs, which yields a further phase-noise improvement.

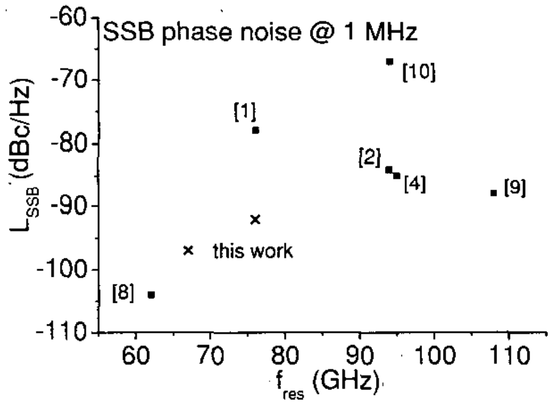

Fig. 7 SSB phase noise data at 1 MHz offset against frequency for published MMIC VCOs.

With an additional varactor tuning at the base, the tuning range is increased to 8.6 %. The results demonstrate the potential of GaAs-based HBT-MMICs for low phase-noise W-band oscillators.

Acknowledgement: this work is supported by the German BMBF under contract No. 01BM050.

References

[1] H. J. Siweris, H. Tischer, T. Grave, W. Kellner, "A Monolithic W-band HEMT VCO With Feedback Topology," *1999 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, pp. 17-20, June 1999.

[2] S. Kudszus, W. H. Haydl, A. Tessmann, W. Bronner, M. Schlechtweg, "Push-Push Oscillators for 94 and 140 GHz Applications Using Standard Pseudomorphic GaAs HEMTs," *2001 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 1571-1574, June 2001.

[3] A. Tessmann, S. Kudszus, T. Feltgen, M. Riessle, C. Sklarczyk, W. H. Haydl, "A 94 GHz Single-Chip FMCW Radar Module for Commercial Sensor Applications," *2002 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 1851-1854, June 2002.

[4] Y. Baeyens, R. Pullella, C. Dorschky , J.-P. Mattia, R. Kopf, H.-S. Tsai, G. Georgiou, R. Hamm, Y. C. Wang, Q. Lee, Y.-K. Chen, "Compact Differential InP-Based HBT VCO's with a Wide Tuning Range at W-Band," *2000 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, pp. 349-352, June 2000.

[5] K. Uchida, H. Matsuura, T. Yakihara, S. Kobayashi, S. Oka, T. Fujita, A. Miura, "A Series of InGaP/InGaAs HBT Oscillators up to D-Band," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-49, no. 5, pp. 858-865, May 2001.

[6] M. Schott, H. Kuhnert, F. Lenk, J. Hilsenbeck, J. Würfl, W. Heinrich, "38 GHz Push-Push GaAs-HBT MMIC Oscillator," *2002 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 839-841, June 2002.

[7] H. Kuhnert, F. Lenk, J. Hilsenbeck, J. Würfl, W. Heinrich, "Low Phase-Noise GaInP/GaAs-HBT MMIC Oscillators up to 36 GHz," *2001 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 1551-1554, June 2001.

[8] H. Wang, K. W. Chang, L. T. Tran, J. C. Cowles, T. R. Block, E. W. Lin, G. S. Dow, A. K. Oki, D. C. Streit, B. R. Allen, "Low Phase Noise Millimeter-Wave Frequency Sources Using InP-Based HBT MMIC Technology," *1996 IEEE Journal of Solid-States Circuits.*, vol. 31, pp. 1419-1425, Oct. 1996.

[9] K. W. Kobayashi, A. K. Oki, L. T. Tran, J. C. Cowles, A. Gutierrez-Aitken, F. Yamada, T. R. Block, D. C. Streit, "A 108-GHz InP-HBT Monolithic Push-Push VCO with Low Phase Noise and Wide Tuning Bandwidth," *1999 IEEE Journal of Solid-States Circuits.*, vol. 34, pp. 1225-1232, Sep. 1999.

[10] A. Bangert, M. Schlechtweg, M. Lang, W. Haydl, W. Bronner, T. Fink, K. Kohler, B. Raynor, "W-band MMIC VCO with a Large Tuning Range Using a Pseudomorphic HFET," *1996 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 525-528, June 1996.