# $W$-Band HEMT-Oscillator MMICs Using Subharmonic Injection Locking

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***Abstract*—The efficient stabilization of high electron mobility transistor (HEMT) oscillator monolithic microwave integrated circuits (MMICs) for $W$-band applications, using a new approach of high-order subharmonic injection locking, is presented. Transmission- and reflection-type injection locking techniques are applied to stabilize 94-GHz oscillators based on GaAs pseudomorphic-HEMT technology. A voltage-controlled oscillator MMIC was developed, consisting of the oscillator circuit and an integrated harmonic generator, that can be stabilized by injection power levels of −45 dBm at 94 GHz using reflection-type injection locking, allowing reference frequencies as low as the fifteenth to twenty-first subharmonic as the input for the harmonic generator. Additionally, an injection-locked phase-locked loop (PLL) was developed, which enhances the locking range from 30 MHz to 1 GHz, using the twenty-first subharmonic as a reference signal. The combination of simple synchronization to a low-frequency reference signal and the control of the synchronization in the injection-locked PLL allows the generation of stable and low-noise millimeter-wave signals with a fully integrated MMIC source.**

***Index Terms*—Injection locked oscillators, millimeter wave generation, voltage controlled oscillators, MODFETs, phase noise, monolithic microwave integrated circuits (MMICs), coplanar waveguides.**

## I. Introduction

THE growing interest in millimeter-wave applications up to $W$-band frequencies—for example, radar, automotive cruise control, or broadband communication—raises the demand for highly integrated subsystems including a solid-state signal source. Only a high degree of integration leads to a cost-effective production of subsystems by reducing the number of chips necessary for multichip modules. Pseudomorphic high electron mobility transistors (PM-HEMTs) on GaAs allow easy integration and high-frequency application [1], [2] for mixer and amplifier circuits. Free-running oscillators on GaAs reach high output power levels and allow easy frequency tuning [3] but have poor phase noise performance due to the high $1/f$-noise of the devices and the low $Q$ factor that can be achieved in monolithic microwave integrated circuits (MMICs). Thus, our research focuses on advanced stabilization techniques for oscillators up to $W$-band frequencies to achieve high spectral purity using standard PM-HEMT technology. Our goal is the integration of the signal source in a complete subsystem.

For stabilization of the millimeter-wave signal by synchronization to a high-quality reference at a subharmonic frequency, injection locking [4], [5] or phase-locked-loop (PLL) techniques [6] are commonly applied. Up to now, subharmonic injection locking, demonstrated with $V$- and $W$-band injection locked oscillators (ILOs) [4], [5], employed transmission-type injection locking, where a reference signal at a subharmonic frequency is applied directly at the gate of the transistor of the oscillator. This technique is limited to subharmonic factors of only three to six. Higher order subharmonic references are desired, however, especially for $W$-band oscillators, such that commercially available reference signals below 10 GHz can be used.

In this work, we increased the subharmonic factor for the reference signal significantly, presenting a $W$-band HEMT oscillator MMIC that can be locked by reference signals at the fifteenth to the twenty-first subharmonic. This was achieved by the combination of a new and more effective reflection-type injection-locking technique with a simple harmonic generator, integrated into the oscillator MMIC. This method allows the use of readily available commercial reference sources to realize a stabilized $W$-band signal source module. To account for temperature-dependent variations of the circuit, the oscillator circuit was integrated in an injection-locked PLL (ILPLL) circuit [7]–[9] to ensure stable synchronization of the oscillator output signal. The so-realized ILPLL MMIC improved the locking range from 30 MHz to 1 GHz.

## II. Synchronization of $W$-Band HEMT Oscillators

### A. Direct Injection of a Subharmonic Reference

Subharmonic injection locking is commonly realized by applying a subharmonic reference (injection signal) at the gate of the transistor of the oscillator (transmission-type injection locking). Fig. 1 shows the circuit diagram and a chip photograph of a 94-GHz oscillator with varactor tuning capability and an input port for direct injection locking.

Due to the nonlinearity of the transistor, numerous harmonics are generated in the circuit. The harmonic closest to the free-running frequency of the oscillator can synchronize the oscillator output signal [10], [11]. A typically measured locking range of

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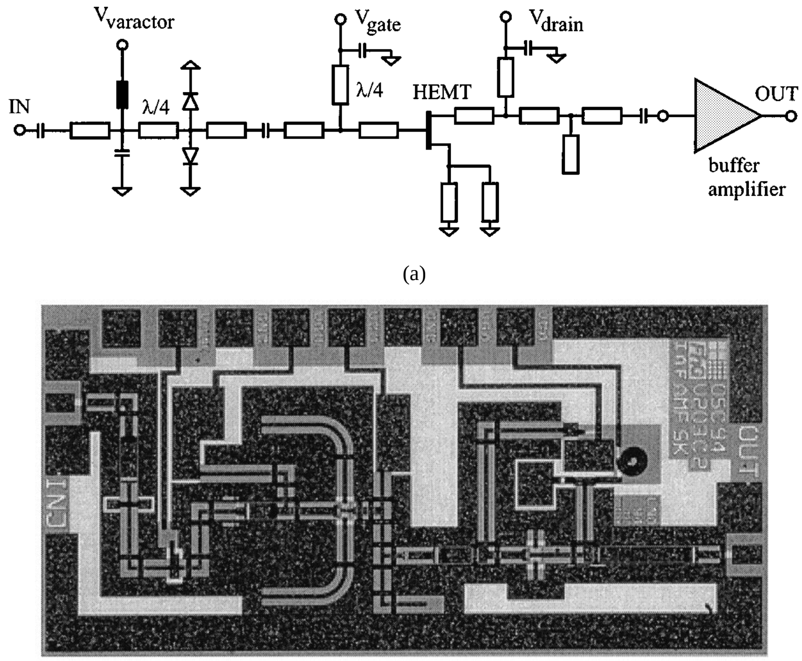



Fig. 1. (a) Circuit schematic and (b) photograph of a 94-GHz oscillator MMIC (chip size 1 × 2 mm$^2$) with direct signal injection.

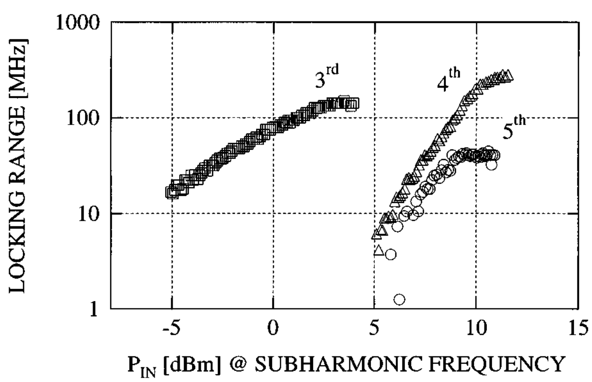



Fig. 2. Measured locking range of the 94-GHz HEMT oscillator MMIC shown in Fig. 1, which employes direct injection locking.

the 94-GHz HEMT oscillator MMIC (Fig. 1) is illustrated in Fig. 2.

The measurement shows that large locking ranges can be achieved for low subharmonic factors. High input power levels are required because of the weak nonlinearity of the transistor, which limits this application to about the sixth subharmonic as the injection signal. The high injection power level causes self-biasing effects at the gate, and the change in the bias condition results in a frequency shift.

### *B. Reflection-Type Injection Locking*

To circumvent the aforementioned disadvantages of the direct injection of the subharmonic reference at the gate, we investigated the locking performance of oscillators [3] applying a new technique (reflection-type injection locking), where the reference signal is now injected at the transistor output, the drain. An injection signal at the drain of the transistor causes only minor changes in the oscillator performance due to the isolation between gate and drain of the device. But there is insufficient non-

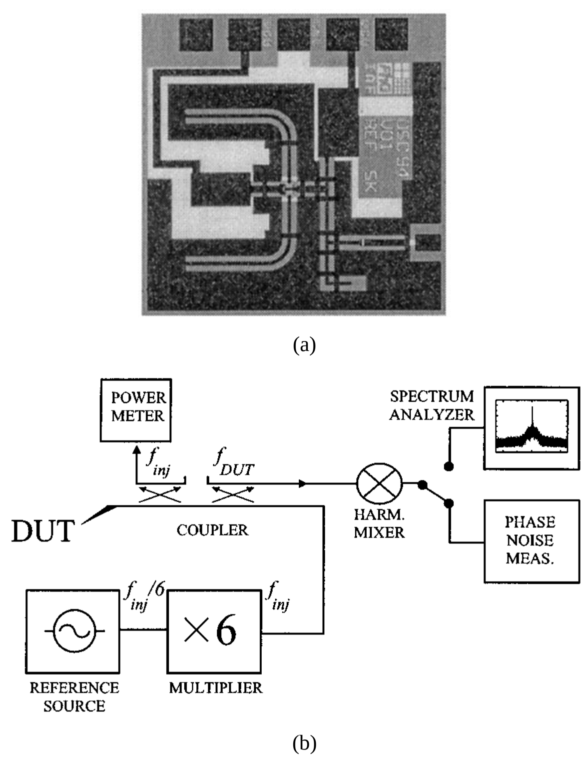



Fig. 3. (a) Chip photograph of the measured oscillator MMIC (chip size 1 × 2 mm$^2$) and (b) measurement setup for reflection-type injection locking.

linearity present to generate harmonics at the output; thus only fundamental locking is possible.

We used a simple $W$-band oscillator MMIC, as shown in Fig. 3(a), which was directly contacted on an on-wafer measurement probe station. The output of the MMIC was connected to the output of a Wiltron 54 000-6WR10 frequency multiplier module, which was fed by an HP83650B synthesizer signal at

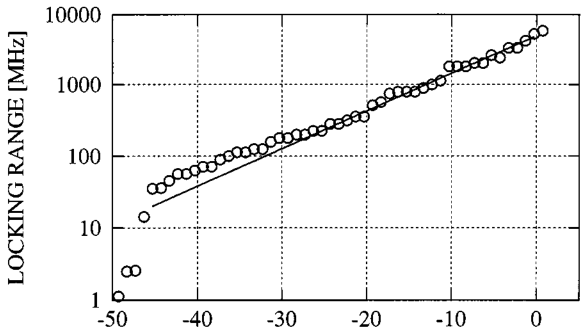



Fig. 4. Measured locking range of the HEMT oscillator using reflection-type injection locking, as shown in Fig. 3, with a reference signal at the fundamental frequency of the oscillator.

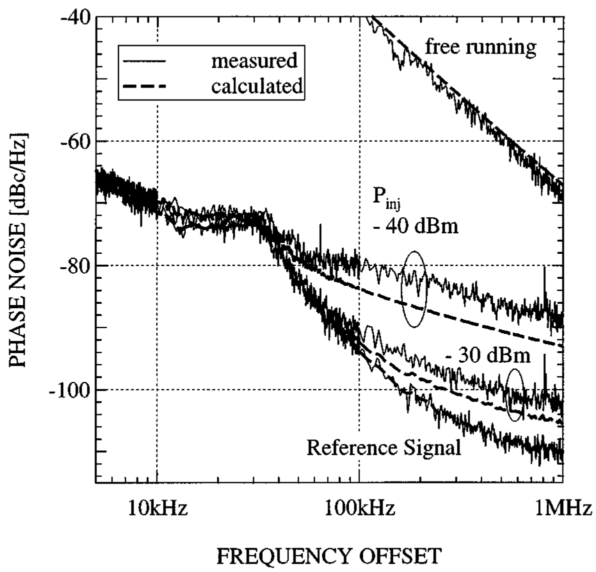



Fig. 5. Influence of the injection power on the phase noise performance of the synchronized output signal of the oscillator.

the sixth subharmonic. The unwanted harmonics are suppressed below −55 dBc using the bandpass filters provided with the multiplier module. A 10-dB directional coupler was used to couple out the oscillator output signal. This measurement setup, as illustrated in Fig. 3(b), was used to determine the locking range of the oscillator and the phase noise performance as a function of the injection power. The measured locking range and its linear approximation are illustrated in the diagram in Fig. 4. This measurement shows that very low injection power levels of about −45 dBm are sufficient to achieve a usable locking range.

The phase noise measurement of the oscillator output signal is illustrated in Fig. 5. According to theory, the phase noise of the synchronized signal is the same as that of the reference signal, for sufficiently high injection power levels. If the power of the reference signal is too small, an increasing difference between reference and output signal [12], [13] can be observed at higher frequency offsets, as shown in Fig. 5. The dependency of the phase noise of the locked output signal was described in detail in [12], and these results are used below to account for the measured degradation. The phase noise $\mathcal{L}_0(\Omega)$ of the free-running oscillator can be calculated from

$$\mathcal{L}_0(\Omega) = \left(1 + \frac{\omega_c}{\Omega}\right) \frac{\Delta\Omega^2}{\Omega^2} \qquad (1)$$

where $\Omega$ is the offset frequency from the carrier, $\omega_c$ is the $1/f$-noise corner frequency of the active device, and $\Delta\Omega$ is a curve fitting factor. We measured the low-frequency noise properties of the PM-HEMT devices used in the circuit, resulting in a high $1/f$-noise corner frequency $\omega_c/2\pi = f_c \approx 3$ MHz. The phase noise measurement of the free-running oscillator compared to the calculation from (1), using the measured $\omega_c$ and fitting $\Delta\Omega$, is shown in Fig. 5.

We can than use the simplified formula from [12] to calculate the phase noise of a synchronized oscillator $\mathcal{L}_{1/n}(\Omega)$

$$\mathcal{L}_{1/n}(\Omega) \approx n^2 \mathcal{L}_{\text{inj}}(\Omega) + \frac{\left(1 + \frac{\omega_c}{\Omega}\right)}{\Delta\omega_{1/n}^2} \Delta\Omega^2. \qquad (2)$$

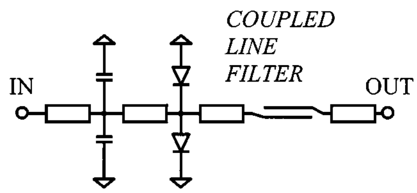
For fundamental injection locking, as used in our experiment, the factor $n$, which describes the subharmonic used as the injected signal, is set to unity. $\Delta\omega_{1/n}$ is the locking range of the oscillator and $\mathcal{L}_{\text{inj}}(\Omega)$ is the phase noise of the injected reference signal. For large locking ranges $\Delta\omega_{1/n}^2 \gg \Omega$, the second term of (2) becomes negligible in most applications, and thus $\mathcal{L}_{1/n}(\Omega) \approx \mathcal{L}_{\text{inj}}(\Omega)$ (with $n = 1$) is expected. But using PM-HEMT devices, the $1/f$-noise corner frequency and the high $\Delta\Omega$ become dominant, resulting in a degradation of the phase noise, even for the large measured locking ranges shown in Fig. 4. Fig. 5 shows the calculated phase noise of the locked oscillator for two injection power levels, using the corresponding locking ranges from Fig. 4, and $\omega_c$ and $\Delta\Omega$ from the calculation of the phase noise $\mathcal{L}_0(\Omega)$ of the free running oscillator from (1), also shown in Fig. 5. Good agreement between measurement and the simple calculation was achieved, accounting for the observed phase noise degradation for offset frequencies above 40 KHz.

## III. Circuit Description and Test Results

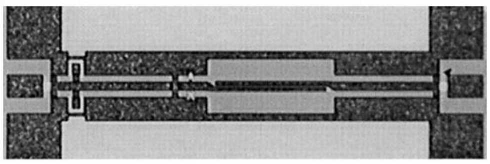
Based on these results, a harmonic generator, using a pair of antiparallel HEMT diodes, was developed to generate the required power level at the oscillator frequency of 94 GHz from subharmonic input signals from 4 to 7 GHz. The generated harmonics are applied at the drain of the transistor to realize reflection-type injection locking. Compared to the direct injection-locking technique, low-frequency reference signals can be used and the influence of the injected signal on the oscillator performance is strongly reduced, due to the seperation of the oscillator circuit from the circuit used for the generation of the harmonics.

### *A. Harmonic Generator*

All MMICs presented in this paper were realized using 0.15-$\mu$m AlGaAs/InGaAs/GaAs PM-HEMTs and coplanar circuit topology. Fig. 6(a) shows the circuit schematic of the simple harmonic generator. The two antiparallel diodes clip the peaks of the input signal and generate harmonics over a wide frequency range. A simple matching structure of shunt capacitances and a short transmission line was used to optimize the output signal power at 94 GHz. A coupled line filter provides the isolation between the low-frequency input and the high-frequency output. An isolation of better than −20 dB was achieved for input signals at frequencies less than 7 GHz. The

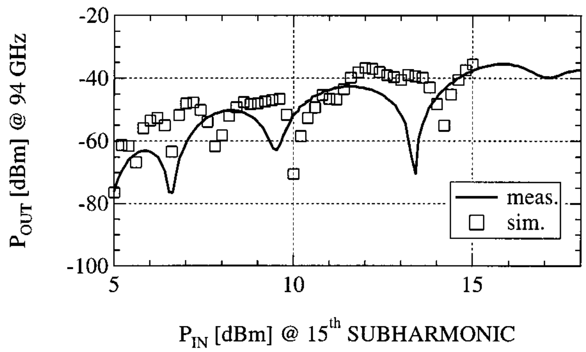



(a)

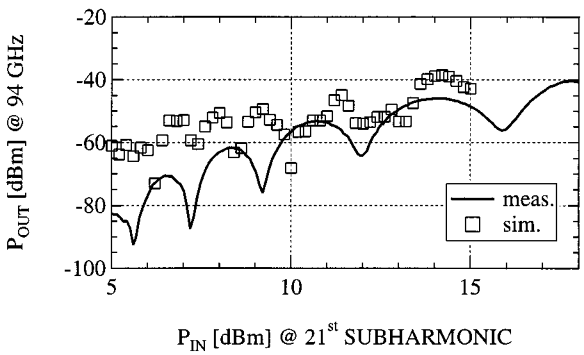


(b)

Fig. 6. (a) Circuit schematic of the harmonic generator and (b) photograph of the test structure.



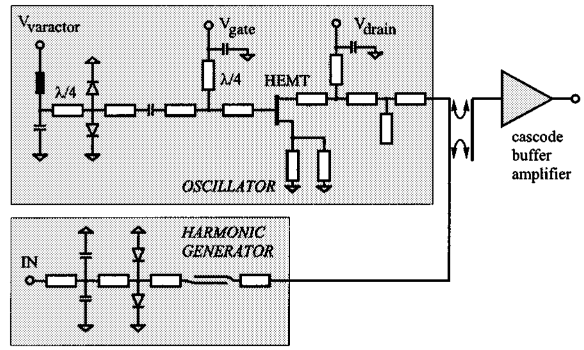

(a)



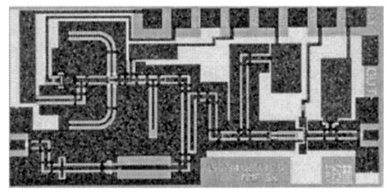

(b)

Fig. 7. Output power at 94 GHz of the harmonic generator versus the (a) fifteenth and (b) twenty-first subharmonic input power levels.

performance of the harmonic generator was measured using the test structure shown in Fig. 6(b). The diagrams in Fig. 7 illustrate the output power level of the harmonic at 94 GHz for an input signal at (a) the fifteenth and (b) the twenty-first subharmonic. An accurate prediction of the output power level is achieved by a harmonic balance simulation even at high harmonics, using simple large-signal models for the diodes. The periodic behavior of the output power versus the input power results from the large-signal performance of the diodes in combination with the matching circuit and was optimized to reach a maximum for input power levels of about 15 dBm. An output power of more than $-40$ dBm at 94 GHz was measured, sufficient to be used as the locking signal.




(a)



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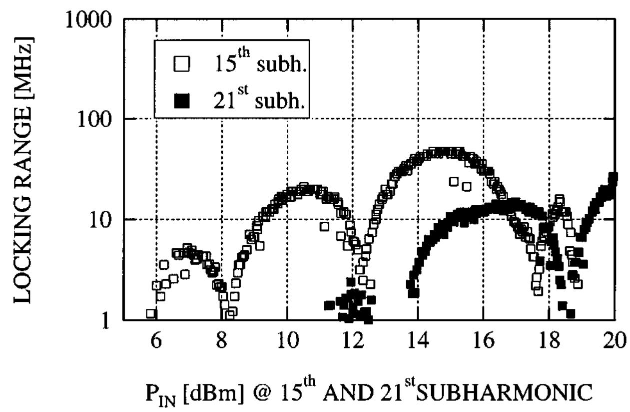
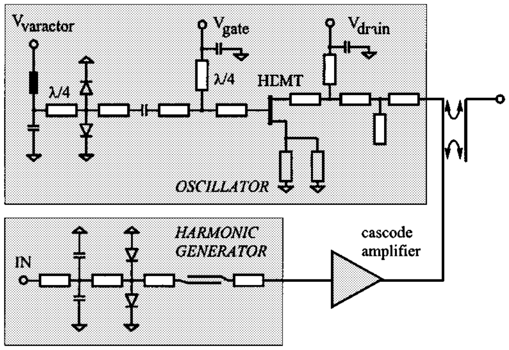



(c)

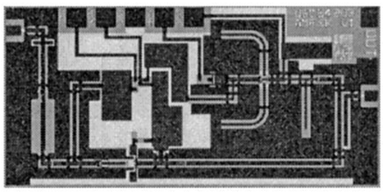
Fig. 8. (a) Schematic circuit diagram and (b) chip photograph of the oscillator MMIC (chip size $1 \times 2$ mm$^2$) with integrated harmonic generator and cascode buffer amplifier. (c) Locking range of the oscillator versus the fifteenth and twenty-first subharmonic input signal power level.

### *B. High-Order Subharmonic Injection-Locked Oscillator*

Fig. 8 shows a schematic circuit diagram and chip photograph of the 94-GHz oscillator MMIC consisting of the oscillator, a cascode buffer amplifier, and the harmonic generator. The output of the harmonic generator is directly connected to the oscillator output, allowing efficient reflection-type injection locking. The coupled lines reject the input signal at lower frequencies. The oscillator uses series feedback at the source of the transistor and allows frequency tuning of more than 6 GHz by the shunt varactor diodes. The oscillator output signal is coupled out with a 10-dB directional line coupler having a center frequency at 94 GHz, which suppresses unwanted spurious signals from the harmonic generator due to its high reverse isolation (better than $-40$ dB for frequencies $< 20$ GHz). A single-stage cascode buffer amplifier [14] provides high isolation of the oscillator circuit from the output of more than 20 dB. The high gain of the compact cascode buffer amplifier compensates for the losses of the coupler. We achieved an output power of typically 4 dBm. We also investigated the spurious frequencies of




(a)



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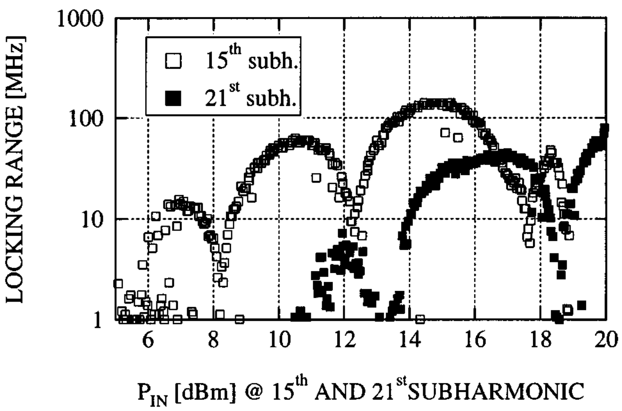



(c)

Fig. 9. (a) Circuit schematic and (b) chip photograph of the second version of the oscillator MMIC (chip size 1 × 2 mm$^2$) with an additional amplifier in the locking path. (c) Measured locking range.

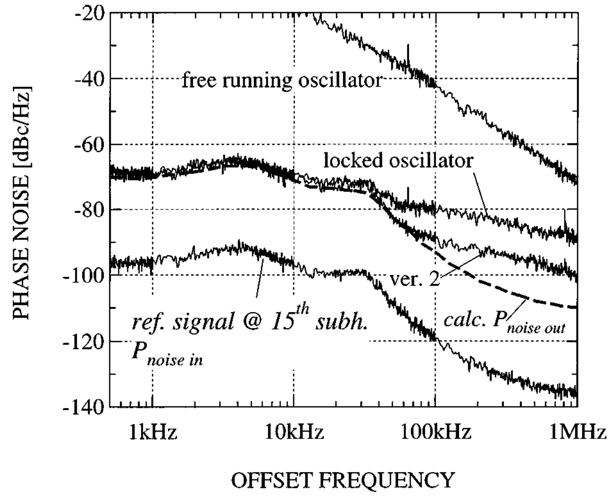



Fig. 10. Phase noise of the free-running and the injection-locked oscillators (locked with the fifteenth subharmonic) compared to the reference signal. The calculated curve represents the theoretical limit of the possible phase noise reduction with this reference, calculated from $P_{\text{noise out}} = N^2 \times P_{\text{noise in}}$, with $N = 15$.

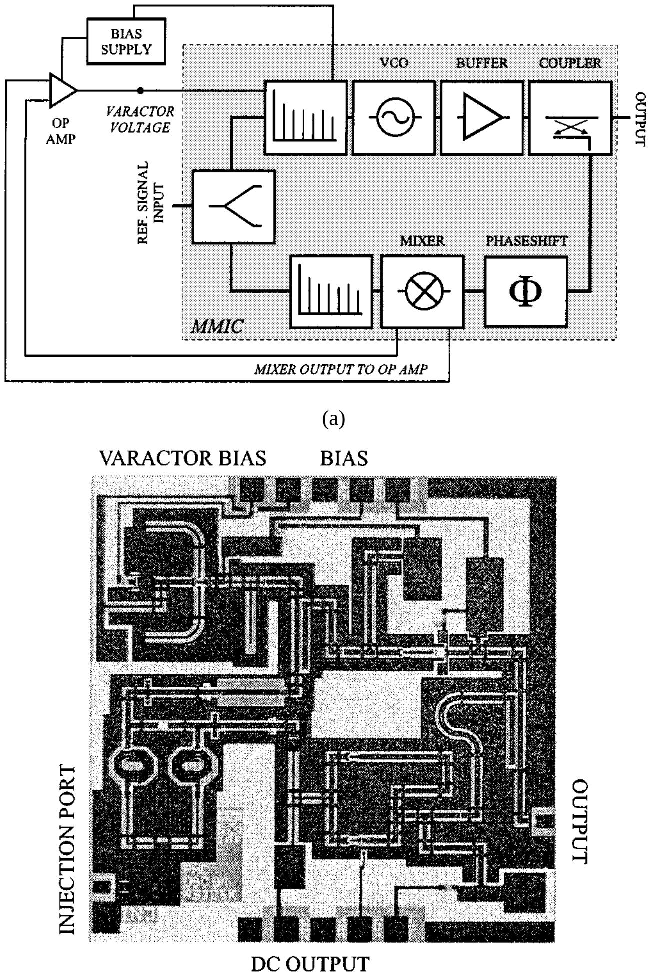
the low-frequency injected signal at the output of the ILO chip. The measured suppression of the injected signal and its harmonics at the output is better than −50 dBc. This high isolation is mainly achieved by the coupled line filter at the output of the harmonic generator and the directional line coupler between the oscillator and the buffer amplifier.

The locking range of the oscillator MMIC versus the injected power, illustrated for the fifteenth and twenty-first subharmonic as a reference signal, is shown in Fig. 8(c). For the fifteenth subharmonic with 15-dBm injected power, a locking range of 50 MHz was measured. To improve this small locking range, we realized a second version of the oscillator MMIC with an additional cascode amplifier in the locking path, as shown in Fig. 9(a) and (b). This amplifier increases the level of the injection signal harmonic, which results in an enhanced locking range of 150 MHz, as illustrated in Fig. 9(c).

The influence of the injection power level can be observed in the phase noise measurement in Fig. 10, illustrating the phase noise performance of the locked oscillator compared to the free-running oscillator and the reference signal. A phase noise of −80 dBc/Hz at 100-kHz offset from the carrier was achieved when locked with the fifteenth subharmonic. The second version achieves a 10-dB reduction of the phase noise at this frequency offset. According to theory [10], [11], the frequency multiplication increases the phase noise as $P_{\text{noise out}} = N^2 \times P_{\text{noise in}}$, where $N$ is the subharmonic factor, predicting 23.5-dB degradation of the phase noise of the oscillator for $N = 15$ and 26.4 dB for $N = 21$, when compared to the phase noise of the subharmonic reference. The calculated curve in Fig. 10 (dotted line) indicates the theoretical phase noise of the oscillator, calculated from the reference signal noise. The degradation is dependent on the offset frequency and the power of the injected signal, as described in Section II. Thus, the second version shows a significant improvement in phase noise, due to a higher injection power level.

## IV. Phase Control of Synchronization

The major problem of any injection-locking technique is the lack of feedback control of the synchronized output signal. Thus, temperature-dependent frequency drifts of the oscillator can result in loss of synchronization, especially when small locking ranges exist. To overcome this problem, we can use the phase relation between the reference input signal and the synchronized output signal of an ILO. Within the locking range, a phase difference from $-\pi/2$ to $+\pi/2$ exists between these signals, as described in [15] and [16]. A zero-degree phase shift specifies the center of the locking range. By detecting this phase relation using a mixer, the dc component is used to control the oscillator output frequency to lie at the center of the locking range, counteracting any frequency drift. This phase control loop was realized in an integrated ILPLL MMIC. The principle of operation of the ILPLL circuit is described in detail in [7]–[9]. The integrated ILPLL chip, using the first version of the oscillator circuit (Fig. 8), is shown in the circuit schematic and the chip photograph in Fig. 11. We used an additional mixer circuit to compare the phase of the input and output signal. The mixing product is obtained directly by RF filtering of the output signal, because the nonlinearity of the HEMT in the




(b)

Fig. 11. (a) Circuit schematic and (b) chip photograph of the injection-locked PLL MMIC.

oscillator already provides the mixer function, as described in [8]. In the approach shown in Fig. 11, all functions of harmonic generation, oscillation, amplification, and mixing are separated into individual circuit blocks to allow optimization of each circuit component. More details on a similar ILPLL circuit, using the fourth subharmonic as a reference signal, are given in [17]. Two harmonic generators are used for this chip, one for the synchronization of the oscillator and one to provide the input signal for the phase comparator, which was realized as a balanced mixer. The measured dc output signal from the mixer, when sweeping the injected signal frequency, is shown in Fig. 12. The peak indicates the locking range of the oscillator. To establish the control of the synchronization, the PLL is closed externally, as shown in Fig. 11(a). The dc output of the mixer is amplified and added to the varactor bias voltage to adjust the oscillator frequency. The locking range of 30 MHz is increased to about 1 GHz using the ILPLL, with the twenty-first subharmonic as the reference signal. The suppression of the low-frequency reference signal and its harmonics is better than −50 dBc, as found for the ILO MMIC from Fig. 8(b).

This approach is well suited for MMIC oscillators due to their strong temperature dependence. The PLL keeps the oscillator at a constant frequency, given by the reference, and the reflection-type injection locking reduces the phase noise of the oscillator, allowing low-frequency reference signals of about 5 GHz.

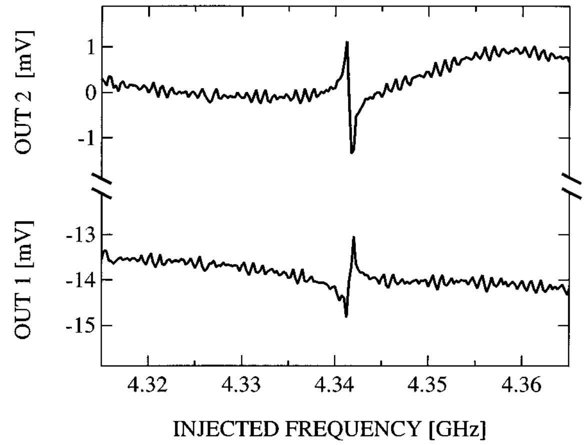



Fig. 12. Measured dc output of the mixer when sweeping the injected signal frequency at the twenty-first subharmonic, without PLL control.

## V. Conclusion

The locking performance of $W$-band HEMT oscillators was investigated. The reflection-type injection locking allows very low input power levels. Less than −45 dBm input signal power at the fundamental frequency was sufficient to synchronize free-running HEMT oscillators. Thus, simple harmonic generators can be used to get the required reference signal from a subharmonic input signal, even at frequencies below 10 GHz. We developed a high-order subharmonic injection-locked oscillator at 94 GHz, based on standard GaAs PM-HEMTs. With the integrated harmonic generator, reference signals at the fifteenth to the twenty-first subharmonic around 5 GHz were used to stabilize the $W$-band oscillator, with a high suppression of −50 dBc of spurious frequencies. An injection-locked phase-locked-loop MMIC was developed. The locking range was improved from 30 MHz without the PLL to 1 GHz using a reference at the twenty-first subharmonic.

The realization of the easy-to-use one-chip solution of a complex system to generate a high-quality millimeter-wave signal shows the potential of integrated HEMT oscillator MMICs. The combination of simple synchronization to a low-frequency reference signal and the control of the synchronization makes this ILPLL MMIC very attractive for further development of millimeter-wave signal sources. Very stable and low-noise signals can be generated by an MMIC source when using the simultaneous injection and phase-locking technique.

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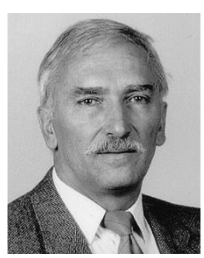

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