Push-Push Oscillators for 94 and 140 GHz Applications Using Standard Pseudomorphic GaAs HEMTs

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***Abstract* — Millimeter wave harmonic oscillators taking advantage of the push-push principle are demonstrated, allowing the use of the second harmonic of the oscillators to extend the applicable frequency range of standard pseudomorphic HEMTs to 94 and 140 GHz. Two configuration schemes are realized. An improved approach using a drain-connected pair of oscillators for efficient and compact circuit design and high output power is presented. Using this approach, oscillators at 94 GHz and 135 GHz were developed, with more than 0 dBm and -2 dBm output power and a high suppression of the fundamental signal of 38 dBc and 20 dBc, respectively. All MMICs were realized in a standard 0.13 µm pHEMT technology using optical stepper lithography.**

I. Introduction

Future demands for compact radar modules with high resolution, push the frequency of operation up to W-band and higher. At high frequencies, the absorption of electromagnetic waves in the atmosphere becomes minimum around 94 and 140 GHz. The low attenuation makes these frequencies particularly interesting for millimeter-wave radar systems. For low cost, the use of MMICs in standard technology is preferable. Thus, we developed signal sources for 94 and 140 GHz, based on an in-house 0.13 µm pHEMT process on 4 inch wafers, using optical stepper lithography, as also shown in [1]. The devices achieve an f_t of 90 GHz and f_{max} of 160 GHz. Coplanar circuit topology was used to avoid backside processing of the wafers and to allow for flip-chip mounting. At frequencies in the W-band and higher, the pHEMTs exhibit only low power-gain, so that the design of fundamental oscillators is very difficult. Thus, we focus on the use and development of harmonic oscillators.

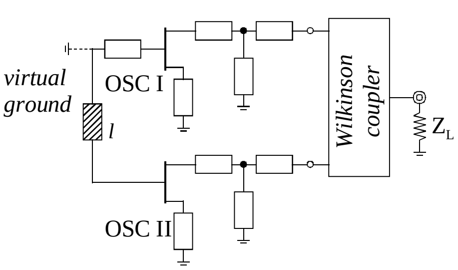


Fig. 1. Circuit configuration of a gate-connected push-push oscillator.

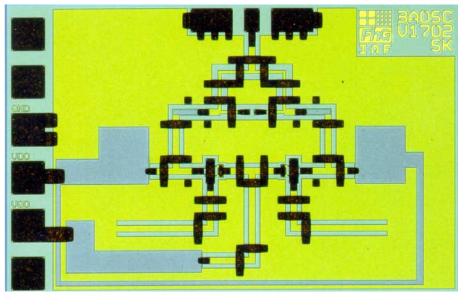


Fig. 2. Chip photo of the gate-connected push-push oscillator for 140 GHz (chip size 1 x 1.5 mm^2).

In this work we investigated and realized different configurations for push-push oscillators. A 140 GHz oscillator using the common push-push design of gate-connected oscillators was realized. Furthermore, an improved approach for compact design and high output power using a drain-connected pair of oscillators was developed. The benefit of this technique is demonstrated by the successful realization of oscillators for 94 and 140 GHz. The presented oscillators and techniques show the potential of the push-push configuration to enhance the frequency range of standard GaAs pHEMTs. All MMICs use our in-house pHEMT technology on GaAs, which is compatible with the Infineon fabrication process [1].

II. Configurations for Push-Push Oscillators

The upper frequency limit of an MMIC oscillator is given by the speed and the high frequency gain of the devices used. To extend the oscillator frequency range, the signal of an oscillator at a lower frequency can be multiplied by an additional circuit, or, use is made of the harmonics generated inherently in the oscillator. A very efficient way to use an oscillator at half the output frequency is the push-push principle [2]. By combining the output signals of two identical oscillator circuits at 180° phase difference, the fundamental frequency is canceled out, and the second harmonics of the oscillators are added constructively. This principle suppresses efficiently the

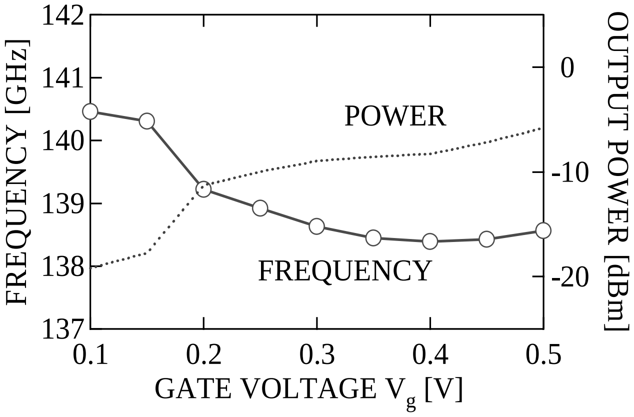


Fig. 3. Measured tuning characteristic of the gate-coupled 140 GHz push-push oscillator.

fundamental signal and thus is well suited for high frequency signal generation.

A. *Gate-connected configuration*

As proposed in [2-5], a push-push oscillator can be described by two identical oscillators, with the input resonance circuits of the transistor (gate or base) connected in parallel to a virtual ground. This configuration is shown in Fig. 1. The transmission line length l between the two oscillators can be used to adjust for a phase difference of 180° between the two oscillators. Each oscillator is terminated by a 50 Ohm load, represented by a Wilkinson combiner at the output frequency. Using this technique, two simple identical oscillators were designed at the fundamental frequency at 70 GHz, which is half of the output frequency. A simple oscillator configuration with series feedback was used [6]. The line length was adjusted to achieve the 180° phase difference between the two oscillators using harmonic balance simulations. The output signals are combined in a Wilkinson coupler with a center frequency at the second harmonic of 140 GHz. The chip photo and the measured output performance of this oscillator is shown in Fig. 2 and Fig. 3. The frequency could be tuned with the gate voltage over 2.5 GHz around the center frequency of 139 GHz. The output power was about -8 dBm. All measurements were performed using a W-band waveguide measurement system. The frequency of oscillation was determined applying harmonic mixing. The output power above 110 GHz was estimated from measurements with a W-band power sensor.

B. *Drain-connected configuration*

The major disadvantage of the technique using a gate connection is the complex circuit design, including a power combiner, resulting in a low output power. A more efficient way to connect the oscillators is the direct

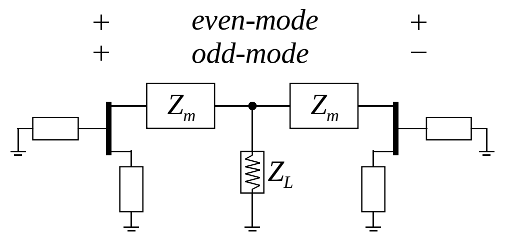


Fig. 4. Direct connection of two oscillators to a common load.

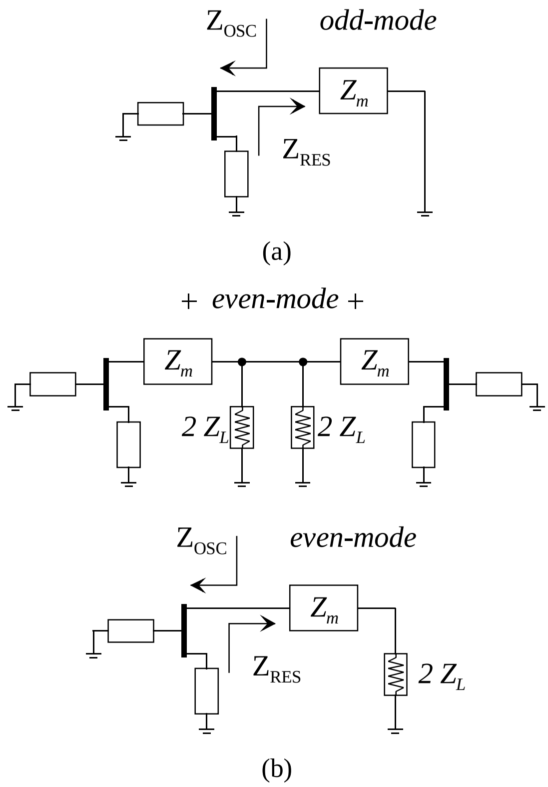


Fig. 5. Simplified equivalent circuits for the odd (a) and the even (b) mode of operation of two oscillators feeding a common load.

connection to a common load impedance. This was applied in [7, 8], but using again the input resonator circuit of the transistor to combine the two oscillators. Due to the feedback, inherent in any transistor, the oscillation conditions have to be fulfilled at the input and output simultaneously. Thus it is also possible to use the output resonance circuit to directly connect the oscillators in parallel to a common load (drain-connected configuration).

In this configuration using a common load, as shown in Fig. 4, the push-push oscillator again can be described by a parallel connection of two similar oscillators in parallel to a virtual ground (for the fundamental frequency). For further explanation, two modes of operation are defined. In the odd-mode, the two oscillators are out of phase and the fundamental signals cancel out. Thus, the circuit can be simplified to the equivalent circuit in Fig. 5(a), by considering one oscillator connected to ground. In the even-mode (for the fundamental frequency of oscillation) the two oscillator signals add in phase. For this mode, we can simplify the oscillator circuit to the equivalent circuit given in Fig. 5(b). In a push-push oscillator, we want to suppress the fundamental frequency. Thus, the oscillators shall operate in the odd-mode, which results in a virtual ground at the load. With the definitions from Fig. 5(a), we obtain eqn. (1) for the start-up condition of oscillation in the odd-mode, ensuring a negative resistance. Equation (2) defines the frequency of oscillation.

$$\mathrm{Re}\{Z_{OSC}+Z_{RES}\} < 0 \quad _{ODD} \qquad (1)$$

$$\frac{d\,\mathrm{Im}\{Z_{OSC}+Z_{RES}\}}{d\omega} > 0 \quad _{ODD}$$

$$\mathrm{Im}\{Z_{OSC}+Z_{RES}\} = 0 \quad _{ODD} \qquad (2)$$

Simultaneously, the unwanted even-mode has to be suppressed to ensure stable odd-mode (or push-push) operation of the oscillator. For this mode, eqn. (3) has to be satisfied, referring to the equivalent circuit in Fig. 5(b).

$$\mathrm{Re}\{Z_{OSC}+Z_{RES}\} > 0 \qquad (3)$$

III. Drain-Connected Push-Push Oscillators

We used the described oscillation conditions to develop a 94 GHz push-push oscillator. First, a simple 47 GHz oscillator was designed. The output matching was used to fulfil eqns. (1)-(3). The simulated impedance for the two modes are illustrated in Fig. 6. The simulation shows, that a negative resistance for the odd-mode allows oscillation in this mode. Any oscillation in the even-mode is suppressed by the positive resistance for this mode. The frequency of oscillation is close to 47 GHz.

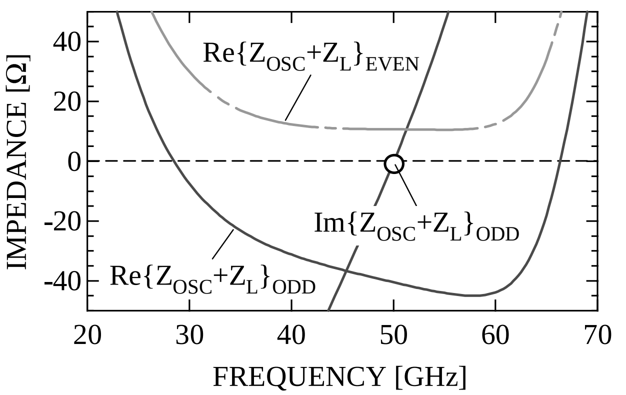
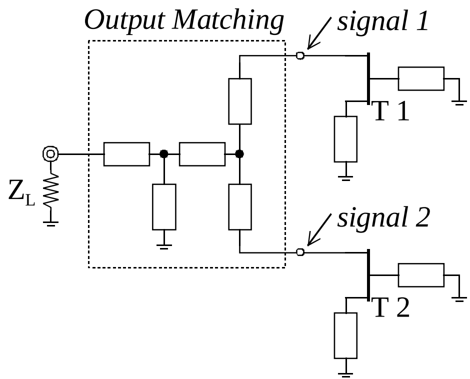
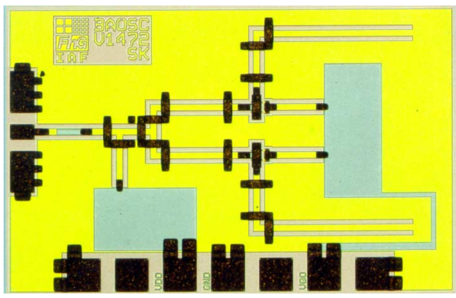


Fig. 6. Simulated impedance for the even and the odd mode operation of the 94 GHz push-push oscillator.

For a more compact design, the two separate output matching circuits of a pair of the 47 GHz oscillators were combined, as shown in Fig. 7(a). Using harmonic balance simulations, the output matching was finally optimized for maximum power at 94 GHz. A chip photo of this oscillator is shown in Fig. 7(b).



(a)



(b)

Fig. 7. Circuit schematic (a) and chip photo (b) of the drain-connected push-push oscillator for 94 GHz (chip size: 1 x 1.5 mm^2).

The measured output spectra at the fundamental and the output frequency at the second harmonic are shown in Fig. 8. More than 1 dBm output power and high suppression of the fundamental of 38 dBc was achieved, showing an accurate 180° phase difference for the two oscillator-branches. The oscillation frequency can be varied within a 3 GHz bandwidth using the gate bias as a tuning voltage, with a degradation of the output power of less than 4 dB. We measured a phase noise of -84 dBc/Hz at 1 MHz offset, but it has to be mentioned, that an integrated output buffer amplifier is crucial for an accurate phase noise measurement.

Applying the same design method, a push-push oscillator for 140 GHz was realized. The chip photo is shown in Fig. 9. An output power of about 0 dBm was estimated.

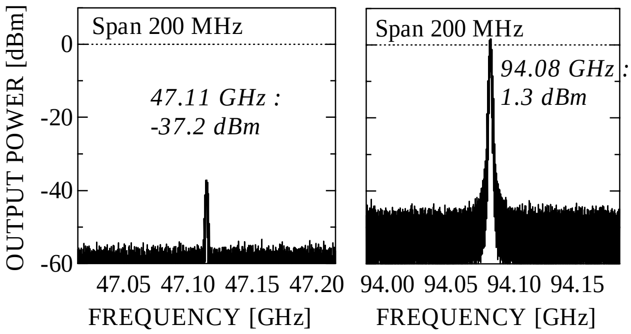


Fig. 8. Measured spectra of the 94 GHz push-push oscillator at the fundamental and the 2nd harmonic output frequency. The deviation from the 2nd harmonic is due to slightly different mismatch of the on-wafer probes for each frequency band.

The fundamental frequency is efficiently suppressed, with a measured output power of only -25 dBm. The oscillation frequency can be tuned within a 4 GHz bandwidth, with a center frequency of 135 GHz, as illustrated in Fig. 10.

IV. Conclusion

Push-push oscillators for 94 and 140 GHz were realized. An improved method for realizing push-push oscillators is presented, using a drain-connection configuration, leading to higher output power, circuit simplicity and small chip size. The developed MMICs demonstrate the expansion of the frequency band of operation of signal sources based on standard pHEMT technology. In combination with recent results on high frequency amplifiers [9], these oscillators offer the possibility of realizing fully integrated sub-systems, as already demonstrated for 94 GHz FMCW applications [10], even at 140 GHz, using GaAs pHEMTs.

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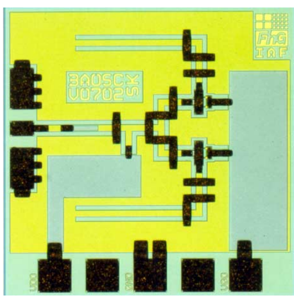

Fig. 9. Chip photo of the drain-coupled push-push oscillator for 140 GHz (chip size: 1 x 1 mm^2).

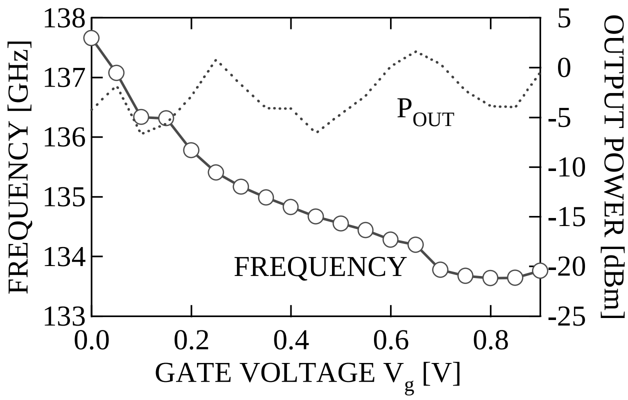

Fig. 10. Measured tuning characteristic of the drain-connected push-push oscillator for 140 GHz.

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