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A varactor tuned low-cost 24 GHz harmonic VCO

M. O. Olbrich, L. Huang, and E. M. Biebl

Fachgebiet Höchstfrequenztechnik, Technische Universität München, 80290 München, Germany

Abstract. We present a low-cost 24 GHz VCO that is based on a microstrip design combined with discrete packaged devices. The output frequency is generated by a harmonic oscillator. The tunabilty was reached using a varactor diode. Two versions of the VCO were built, one has a wide tuning range of 1.1 GHz and the other one has a high output power of 3.7 dBm.

1 Introduction

A voltage controlled oscillator is the key component in various microwave systems. Tunability of these VCOs is essential in many systems, e.g. in FMCW radars. Moreover fabrication variations or temperature drift can easily be compensated by using VCOs.

For the 24 GHz ISM-band an increasing number of applications like automotive radar systems or short-range communication links are proposed. Since the current ISM bandwidth specification limits these applications, the FCC and the ETSI put significant effort into expanding the specification for usability for UWB systems. Such systems demand for a moderate fixed frequency output power of a few mW and an ultra-wide tuning range to spread the signal. Tuning speed is also a figure of merit as it directly influences the repetition rate of the overall system. Finally, the usual prerequisite of low cost, as well as ease of fabrication is demanded.

Monolithic integrated solutions with a fractional-N-PLL achieve -6 dBm output power and a tuning range of 500 MHz (Stelzer et al., 2003). A harmonic DRO was published (Jeon et al., 1996) with 5.5 dBm output power at 20.5 GHz and a tuning range of 54 MHz. Another common tuning possibility is a YIG tuned oscillator. In Khanna and Hauptman (1991) a YTO is published from 18 GHz to 40 GHz with an output power of 13 dBm including integrated amplifiers.

Our approach to meet the above mentioned requirements is to integrate microstrip structure design with SMD handling compatible discrete packaged active devices. Furthermore, we take advantage of the generally present harmonics in the transistor of the oscillator. This is common practice to gain RF output power, generated at moderate frequencies where low-cost devices are available. The tunabilty was reached using a varactor diode.

2 Principle

Packaged devices are rarely available at 24 GHz due to the parasitics. And accordingly, low parasitics packages yield considerably more expensive devices. To bypass this barrier, a common solution is to generate the oscillation at lower frequencies where adequate devices are available, before mixing the signal to the desired frequency. This can be done by separate elements, or as shown in our design within one element. Harmonics are present in any oscillator due to the nonlinearities of the active element. The principle of a harmonic oscillator is to reflect the power at the fundamental frequency back into the device and to get maximum output power at the desired harmonic.

The oscillator design is based on the one-port approach. The transistor circuit has to fulfill the oscillation conditions

$$|\Gamma_A| \cdot |\Gamma_P| = 1 \qquad (1)$$

and

$$\angle\Gamma_A + \angle\Gamma_P = 2\pi n, n = 0, 1, 2, ... \qquad (2)$$

at the fundamental frequency, with the reflection coefficients $|\Gamma_A|, |\Gamma_P|$ of the active and the passive part. According to Chua et al. (1987) this criterion can be replaced by the Nyquist plot analysis. The circuit is unstable if the Nyquist loop $(\Gamma_A \cdot \Gamma_P)$ encircles the point $1 + j0$ in clockwise direction. The separation plane is set at the source pin of the tran-

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Correspondence to: M. O. Olbrich (olbrich@tum.de)

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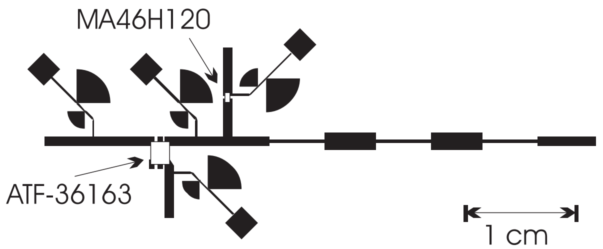

Fig. 1. Layout of the maximum power VCO.

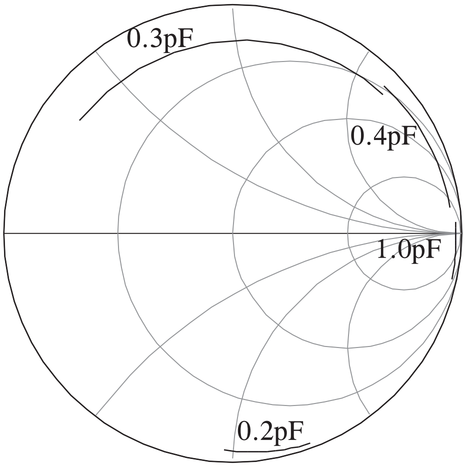

Fig. 2. Reflection coefficient of the passive part for several varactor capacitances (11.9–12.1 GHz).

sistor. The magnitude of Γ_A is an indicator for the achievable output power. The reflection coefficient of the the active part is influenced by the circuit at the gate and drain connectors of the transistor. The transistor is modeled by its s-parameters given by the manufacturer. The given two-port s-parameters were converted into three-port s-parameters according to Khanna (1985) to gain an additional degree of freedom for the design.

In addition to the oscillation condition at the fundamental frequency, the matching condition ($|\Gamma_A| = |\Gamma_P|^*$) has to be fulfilled at the harmonic frequency to achieve high output power.

According to the oscillation criteria there are two ways to tune the oscillator: Varying either the passive or the active part. Our tuning approach is to change the phase by using a varactor diode. The diode is preferable a packaged device that can be handled with standard SMD fabrication technologies. Since its influence at 24 GHz decreases with increasing capacitance, a diode with low capacitance is required. Therefore the M/A-COM MA46H120 GaAs hyperabrupt varactor diode, with a capacitance from 1.1 pF to 0.14 pF is chosen. Taconic TLP-5-0100 substrate is used. The transistor in the design is an Agilent GaAs PHEMT ATF-36163.

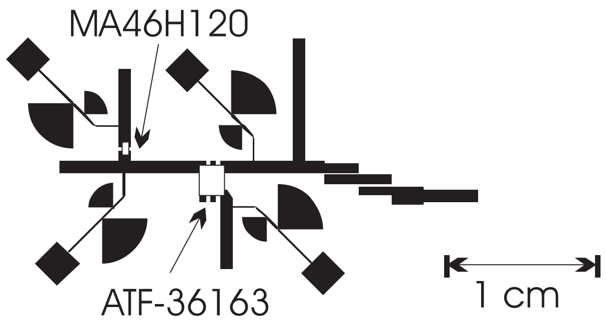

Fig. 3. Layout of the maximum tuning range VCO.

3 Design

We present two different designs. One, referred to as maximum power VCO, was designed for high output power. The other one, referred to as maximum tuning range VCO, showed a high tuning range. The main difference in the design is the location of the varactor diode. In both designs the varactor diode is connected to a virtual ground provided by a $\lambda/4$ transformation in order to keep the biasing effort moderate.

The bias network has to be designed for rejecting the fundamental frequency and the harmonic. This is accomplished by the combination of two radial stubs in each bias network as shown in Fig. 1. The rejection of the fundamental frequency and the matching of the 1st harmonic is done by means of a microstrip filter structure.

3.1 Maximum power VCO

Figure 1 shows the layout of the VCO optimized for maximum power output. A stepped impedance bandpass filter satisfies the oscillation and matching conditions. The varactor diode is attached to this filter, equivalent to the passive part. Thus, the ground bias supplies both, the diode and the source of the transistor. Figure 2 shows a plot of the varactor tuned reflection coefficient of the passive part at the fundamental frequency. Tuning the voltage across the varactor diode results mainly in a displacement of the phase for a frequency point.

3.2 Maximum tuning range VCO

Figure 3 shows the layout of the VCO that exhibits the maximum tuning range. A parallel-coupled, strip-line bandpass filter satisfies the oscillation and matching conditions at the passive part. The varactor diode is attached to the drain stub of the transistor at the active part. In this design, the reflection coefficient of the passive part is fixed, whereas the reflection coefficient of the active part varies with phase and magnitude as shown in Fig. 4.

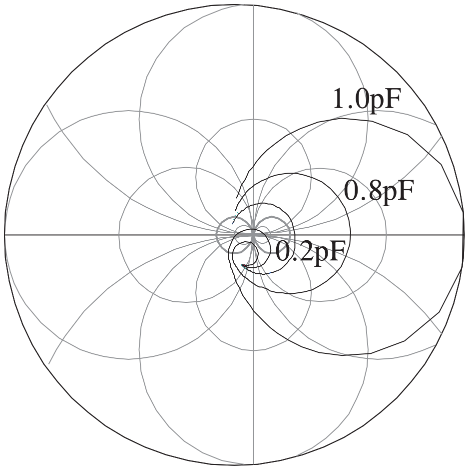

Fig. 4. Reflection coefficient of the active part for several varactor capacitances (11.5-12.5 GHz).

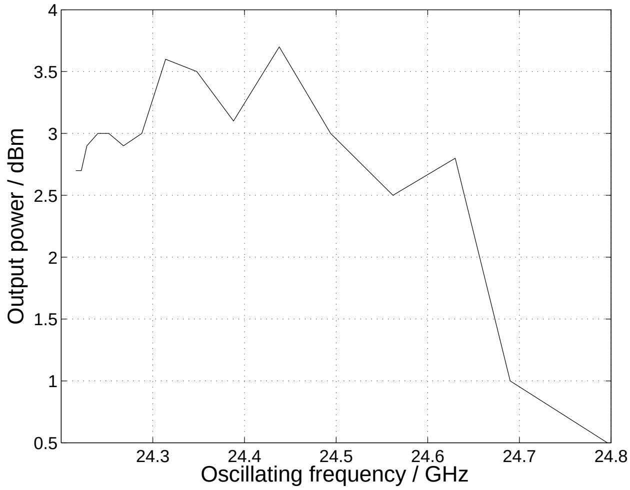

Fig. 5. Output power vs. oscillating frequency of the maximum power VCO.

4 Measurements

All measurement data was taken by a spectrum analyzer. The modulation bandwidth was determined by applying a rectangular signal. A waveform generator provides respective voltages for two oscillation frequencies to the varactor diode. The maximum modulation bandwidth is identified at the 3 dB drop of the output power at a certain oscillation frequency when increasing the modulation frequency.

4.1 Maximum power VCO

The design optimized for maximum output power has a peak power of 3.7 dBm and variations of 3.2 dB over its tuning range of 580 MHz, see Fig. 5. A higher frequency shift is reached for low varactor capacitances, see Fig. 6. The phase noise is -90 dBc/Hz for 1 MHz offset. The modulation bandwidth is 2.5 MHz for a frequency shift of 420 MHz, corresponding to 0 V and 13 V at the waveform generator output. The 13 V result in a frequency of 24,63 GHz.

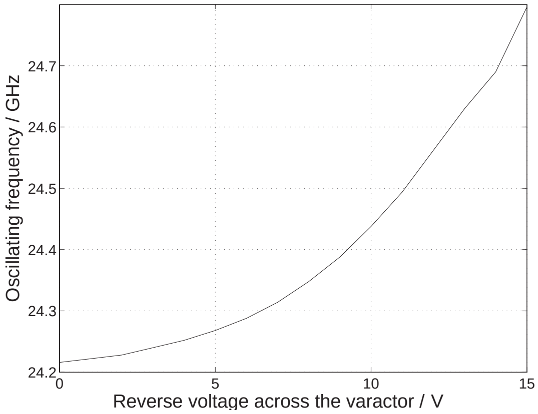

Fig. 6. Oscillating frequency vs. reverse voltage of the maximum power VCO.

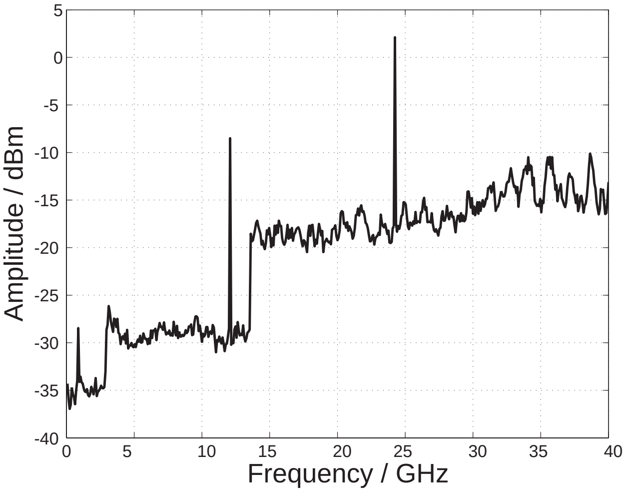

Fig. 7. Output spectrum of the maximum power VCO.

The power variation results from two effects. The capacitance variation of the varactor diode changes not only the phase at the fundamental frequency, but also the matching at the passive part for the harmonic frequency. Additionally, the magnitude of the active part varies over the tuned frequency range, see Fig. 4.

The oscillating frequency is approximately 12 GHz. It is 10 dB below the output power of the 1st harmonic, see Fig. 7.

4.2 Maximum tuning range VCO

The design that showed the maximum tuning range has a tuning range of 1.1 GHz, see Fig. 8. The reverse voltage differs from the other design, since it is superposed with the drain bias of the transistor. The output power varies from -6.2 dBm

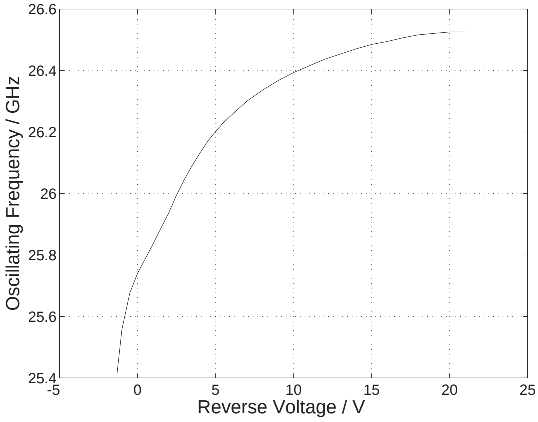

Fig. 8. Oscillating frequency vs. varactor voltage of the maximum tuning range VCO.

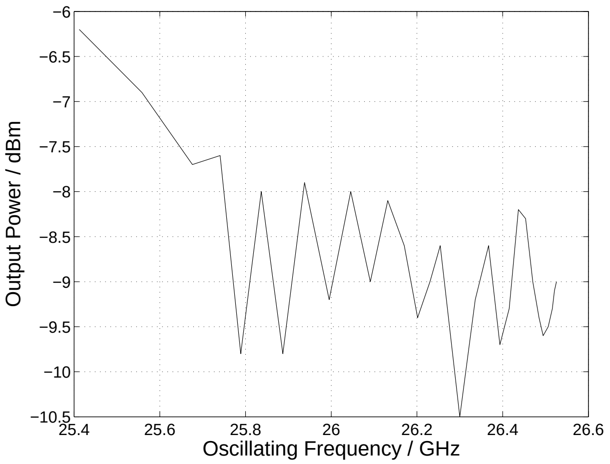

Fig. 9. Output power vs. oscillating frequency of the maximum tuning range VCO.

at 25.4 GHz to -9 dBm at 26.5 GHz, see Fig. 9. Its phase noise is -87 dBc/Hz for 1 MHz offset. The modulation bandwidth is 1.5 MHz for a frequency shift of 900 MHz, corresponding to 3 V and 16 V at the waveform generator output. The 16 V result in a frequency of 26,44 GHz.

The reduction of the output power with increasing frequency corresponds to the simulated reduction of the magnitude as shown in Fig. 4. Additionally, the matching of the harmonic degrades. The spectrum is plotted in Fig. 10. This design results in a 2nd harmonic oscillator with a fundamental frequency at approximately 8 GHz. Though this effect was not designated it was repeatable and stable. The 1st harmonic at about 16 GHz is 9 dB below the output power. Since the frequency shift is converted to the respective harmonics and the influence of the capacitance is more distinct at lower frequencies, the higher tuning range and the lower output power compared to the maximum power VCO design are evident.

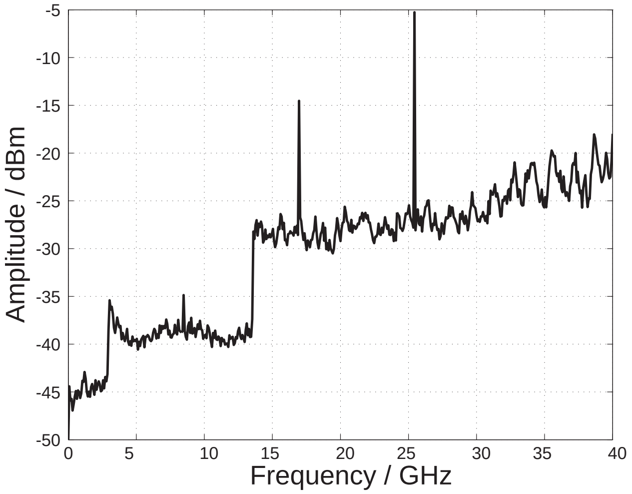

Fig. 10. Output spectrum of the maximum tuning range VCO.

5 Conclusions

We have presented two versions of a 24 GHz varactor tuned harmonic VCO. One exhibits a high tuning range of 1.1 GHz and an output power of -6 dBm. The other one exhibits a lower tuning range of 580 MHz with a higher output power of 3.7 dBm. For the application as a synthesizer in a FMCW radar, the required linearity of the voltage across the varactor diode and the output frequency can be achieved by using a compensation network.

An enhancement of the tuning range can be achieved by tuning the active and the passive part, analogical the matching can be aligned to keep the output power more constant.

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