A Low Phase Noise Silicon 9 GHz VCO and an 18 GHz Push-Push Oscillator

Laurent Dussopt, Denis Guillois* and Gabriel M. Rebeiz
Radiation Laboratory, University of Michigan, Ann Arbor, MI 48109-2122, USA.
*Thales Microwave, Massy, 91349, France
dussopt@engin.umich.edu, rebeiz@umich.edu.

Abstract — **The design and measurement of a Voltage Controlled Oscillator (VCO) at 9 GHz and a push-push oscillator at 18 GHz are described in this paper. Both oscillators use a packaged silicon transistor (Siemens BFP 540F). The microstrip resonator is tuned with a GaAs varactor diode (M/A-COM ML46580). A 270 MHz tuning range is obtained with an output power varying from 3.2 to 8.7 dBm. The phase noise is below -109 dBc/Hz at 100 kHz offset and below –129 dBc/Hz at 1 MHz over the whole tuning bandwidth. The push-push oscillator shows a phase noise of -108 dBc/Hz at 100 kHz and below -124 dBc/Hz at 1 MHz from the carrier. These are, to our knowledge, one of the best phase noise from a silicon fixed or voltage-controlled oscillators using a packaged device at X to K-band frequencies.**

I. Introduction

The increasing demand for C- to K-band communication systems has leaded to a large amount of research in the domain of low-cost and low phase noise VCO's. The principal requirements for the design of low phase noise oscillators are a high quality factor resonator and a low 1/f noise active component.

1/f noise up-conversion has been identified as one of the main contributors to near-to-carrier phase noise [1,2] and the use of bipolar transistors is therefore preferable to GaAs MESFET or HEMT. The push-push configuration is an attractive way to extend the frequency domain of operation of the transistor and has been demonstrated by several authors [3,4]. The push-push oscillator presented in this paper exhibits a very low phase noise at 18 GHz using a simple packaged silicon transistor.

A high-Q resonant circuit is generally provided by a dielectric resonator coupled to a microstrip line. The unloaded Q is typically greater than 500 resulting in excellent phase noise performances at the expense of poor tunability [5]. Alternative resonators such as micro-machined cavities and suspended microstrip resonators have also been investigated for millimeter wave applications with unloaded Q's beyond 450 and planar integration capability [6].

This paper presents two circuits using a λ/2 microstrip resonator with an unloaded Q of 170 at 9 GHz. The VCO is tuned by a varactor diode weakly coupled to the resonator (Fig. 1b)[7], providing a tuning range of 270 MHz while still maintaining a high loaded Q (>50) and a very low phase noise performance.

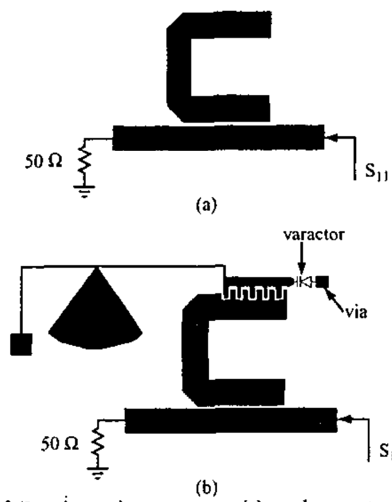


Fig. 1. λ/2 microstrip resonator (a) and varactor-tuned λ/2 microstrip resonator (b).

II. Voltage-Controlled Oscillator Design

Figure 1 shows the λ/2 microstrip resonator coupled to a microstrip line in a fixed-frequency and tunable configuration. The design is performed with HP-Momentum for a resonant frequency of 9 GHz on a 15 mils Duroid substrate. The 50 Ω microstrip line width is 1.15 mm and the gap between the line and the resonator is 100 μm.

The tunable configuration uses a GaAs beam-lead varactor diode M/A-COM ML46580 with a minimum capacitance of C_{18} = 173 fF for a bias voltage V_T = 18 V and a capacitance ratio $C_{18}:C_2$ = 1:8.7. These characteristics have been measured at 9 GHz and are in

0-7803-7239-5/02/$10.00 © 2002 IEEE

good agreement with the data given by the manufacturer. The varactor is weakly coupled to the resonator with a 100 µm-gap interdigitated capacitor (Fig. 1b).

Figure 2 shows the resonant frequency and quality factors (loaded and unloaded) of the tunable resonator for a varactor bias ranging from 2 to 18 V. The tuning bandwidth is 320 MHz (3.55 %). The measured quality factors of the fixed-frequency resonator (Q_l = 61, Q_u = 170) and the tunable resonator with V_T = 18 V (Q_l = 60, Q_u = 143) are very similar because of the small varactor capacitance and the weak coupling between the varactor and the resonator. The series resistance of the diode has been measured at 9 GHz and varies from 4 Ω for V_T = 18 V to 6.2 Ω for V_T = 6 V. Therefore, for bias voltages greater than 6 V, the loaded Q of the resonator is greater than 50 thus allowing oscillation with an acceptable phase noise level.

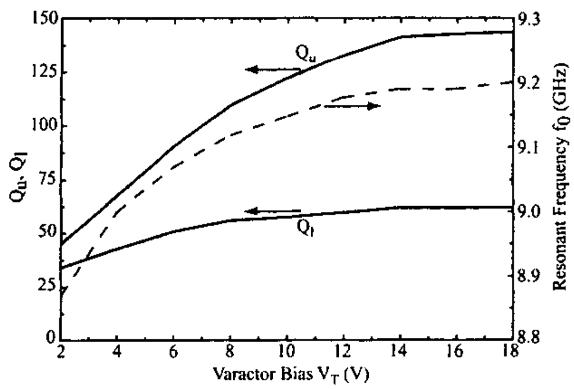


Fig. 2. Measured resonant frequency and extracted loaded and unloaded quality factors of the tunable resonator.

The S-parameters of the packaged transistor with a grounded emitter have been measured at 5–12 GHz on a 15 mils Duroid substrate using TRL calibration techniques. These measurements take into account the packaging parasitics, the via-hole inductance to ground at the source, and the small delay lines at the gate and collector ports of the transistor. The measurements indicate a maximum available gain of 3.7 dB at 9 GHz (V_{ce} = 2 V, I_c = 25 mA)(S_{11} = 0.38, S_{21} = 1.53, S_{12} = 0.33, S_{22} = 0.09).

The oscillator is designed with the method outlined in [6] using the software Agilent-ADS. A non-linear model of the transistor was deduced from the measurements mentioned previously. The source stubs are tuned to achieve instability at 8-10 GHz. The output matching network is designed to optimize the negative resistance at 9 GHz so as to extract the maximum output power from the transistor. Next, the line length between the resonator and the base is tuned to fulfill the phase oscillation condition. The layout of the VCO with the tunable resonator is shown in Figure 3a. The total area is 260 mm^2.

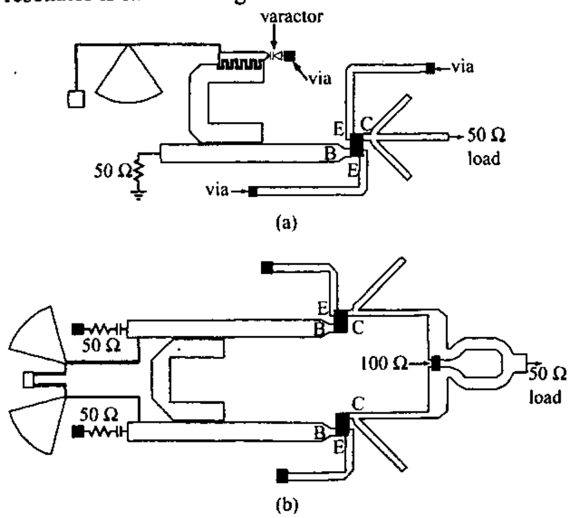


Fig. 3. VCO (a) and push-push oscillator (b) layouts. The transistors are biased through bias tees not represented on the figure.

III. Push-Push Oscillator Design

A push-push oscillator has been designed using the same resonator and transistor for operation at 18 GHz. The layout is shown in Figure 3b. The circuit can be considered as two coupled oscillators working out of phase at 9 GHz. A 180°-coupling is provided by the resonator ensuring out of phase operation. The output signals of both oscillators are added through a Wilkinson power combiner so that the fundamental and odd harmonics cancel out while even harmonics add in phase, resulting in an 18 GHz output signal.

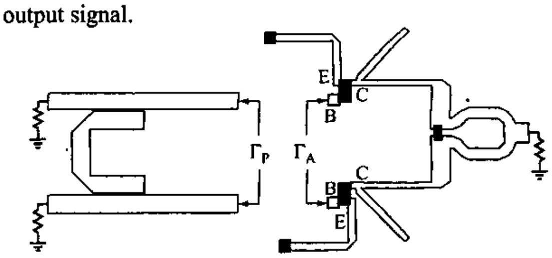


Fig. 4. Push-push oscillator design by the reflection coefficient method.

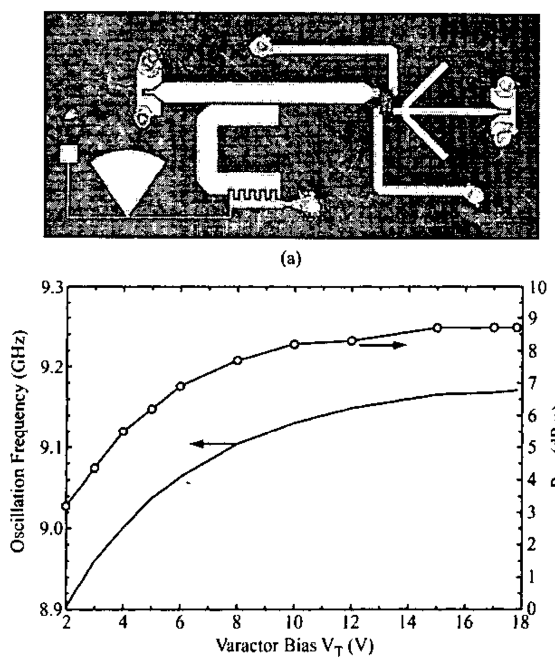
An accurate design however cannot be carried out with the assumption of two independent 9 GHz oscillators since one oscillator affects the impedance of the resonator seen by the other. The circuit is split in a passive part including the resonator and an active part including the transistors and the output circuits. Both parts are treated as one-port circuits with a differential port (Fig. 4). Each part is designed in order to fulfill the oscillation condition [8]:

$$\overline{\Gamma}_P \cdot \overline{\Gamma}_A = 1$$

where $\overline{\Gamma}_P$ and $\overline{\Gamma}_A$ are the reflection coefficients of the passive and active part respectively. $\overline{\Gamma}_A$ depends on the amplitude because of the transistors non-linearity and is therefore calculated with a large signal simulation.

IV. Results and Discussion

First, a 9 GHz oscillator has been tested with a fixed-frequency resonator. The current consumption is 45 mA from a 4 V supply. The high collector current is needed so as to result in a large g_m and therefore high gain at 9 GHz. The measured output power is 8 mW, resulting in a conversion efficiency of 4.5 %. The measured phase noise is –112 dBc/Hz at 100 kHz offset and –129.4 dBc/Hz at 1 MHz offset. These results compare well with those presented in [9] for a similar device and a high-Q dielectric resonator.



(a)

(b)

Fig. 5. VCO photograph (a) and measurements (b): oscillation frequency and output power vs varactor bias.

The VCO results in a tuning range of 270 MHz (3%) with a maximum output power variation of 5.5 dB (3.2–8.7 dBm) for a varactor bias ranging from 2 to 18 V (Fig. 5). Figure 6 shows the phase noise measurements for three different varactor bias (V_T = 6, 10 and 18V), compared to the phase noise of the fixed-frequency oscillator. A simplified model of the oscillator phase noise is given by [10], and for frequencies near the carrier, the phase noise is proportional to $1/Q_l^2$. According to the resonator Q measurements (Fig 2):

$$\frac{Q_l(V_{bias} = 18V)}{Q_l(V_{bias} = 6V)} \approx \frac{60}{50}$$

and therefore the VCO phase noise variation should be around 1.6 dB and agrees well with the measurements of Fig. 6 (-109.3 – -112 dBc/Hz at 100 kHz offset for V_T = 6–18 V).

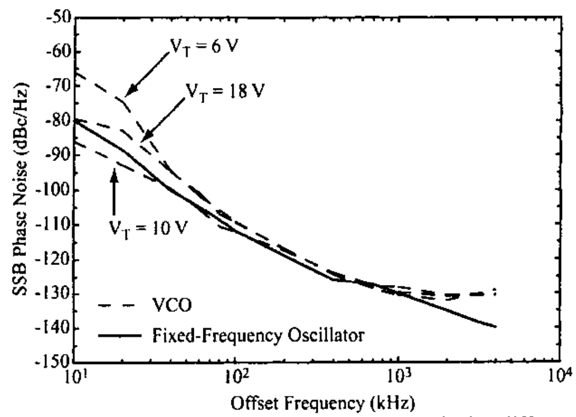


Fig. 6. Phase noise measurements of the VCO for different varactor bias (V_T) and a fixed-frequency oscillator (no varactor) at 9 GHz.

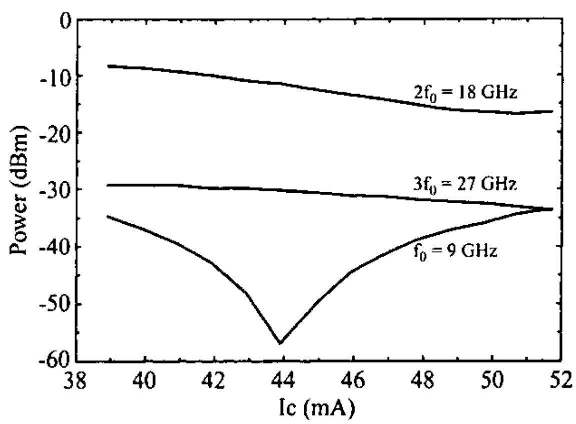
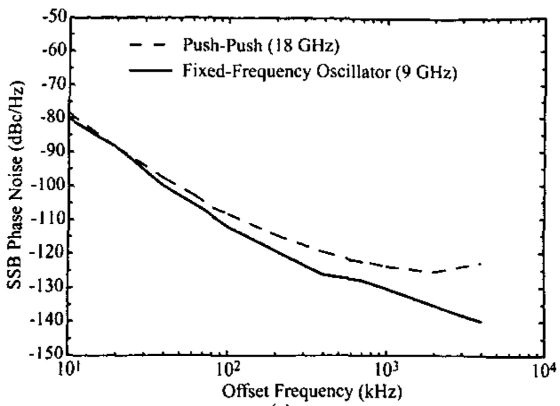


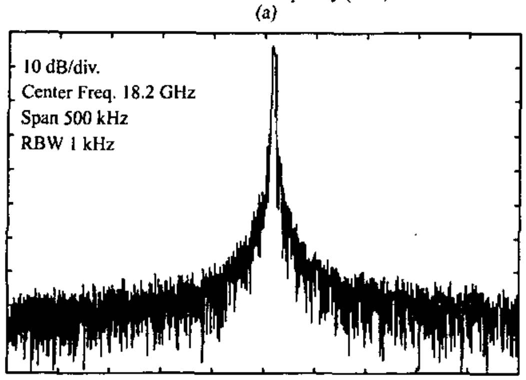
Fig. 7. Output power of the fundamental and harmonics of the push-push oscillator (V_{ce} = 2.4 V).

The output power of the push-push oscillator has been measured and results in -8.3– -16.5 dBm at 18 GHz for V_{ce} = 2.4 V and I_c = 39–52 mA (Fig. 7). The fundamental rejection is bias dependent and greater than 30 dB for I_c = 41–46 mA. This bias dependence is attributed to the slight differences between the transistors and the dis-symmetry in the microstrip circuit due to the fabrication.

The phase noise is −108 dBc/Hz at 100 kHz from the carrier and is lower than −124 dBc/Hz at 1 MHz offset (Fig. 8a). The measurements above 1 MHz offset are limited by the noise floor of our measurement set-up, which is roughly −128 dBc/Hz. The output spectrum at 18 GHz is shown in Fig. 8b.



(a)



(b)

Fig. 8. Phase noise measurements of the push-push oscillator at 18 GHz compared to a fixed-frequency oscillator at 9 GHz (a), output spectrum of the push-push oscillator (b).

The 18 GHz push-push oscillator can be extended to a VCO design with the use of a novel varactor coupled resonator (Fig. 9). The performance of the push-push VCO will be presented at the conference.

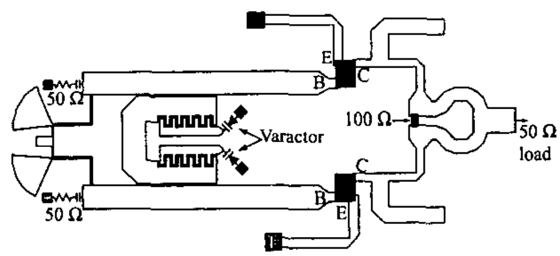


Fig. 9. Layout of the push-push VCO.

ACKNOWLEDGEMENT

The authors thank Dr. Ian Gresham at M/A-COM Tyco Electronics for his help in the phase noise measurements.

REFERENCES

[1] H. J. Siweris and B. Schick, "Analysis of noise upconversion in microwave FET oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 3, pp. 233-242, Mar. 1985.

[2] H. Rohdin, C. Y. Su, and C. Stolte, "A study of the relation between device low frequency noise and oscillator phase noise," *1984 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 267-269, 1984.

[3] F. X. Sinnesbichler, "Großsignalmodellierung von SiGe-hetero-bipolartransistoren für den entwurf von millimeterwellen-schaltungen", PhD thesis, Technischen Universität München, 2000.

[4] D.M. Smith, J.C. Canyon, and D.L. Tait, "25-42 GHz GaAs heterojunction bipolar transistor low phase noise push-push VCOs," *1989 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 725-728, 1989.

[5] X. Xu and R. Sloan, "Improved tuning prediction for the microstrip coupled dielectric resonator using distributed coupling," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-49, no. 3, pp. 553-555, Mar. 2001.

[6] A.R. Brown and G.M. Rebeiz, "A Ka-band micromachined low phase-noise oscillator," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-47, no. 8, pp. 1504-1508, August 1999.

[7] R. Alm, "Radio-frequency oscillator having capacitively-coupled variable reactance device, US patent 6057741, 2000.

[8] P. G. Wilson and R. D. Carver, "An easy-to-use FET DRO design procedure suited to most CAD programs," 1989 *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1033-1036, 1989.

[9] Siemens application note, "SIEGET®25 Silicon Bipolar-dielectric resonator oscillator (DRO) at 10 GHz".

[10] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, no. 2, pp. 329-330, Feb. 1966.