A Low Phase Noise Silicon 18-GHz Push-Push VCO

Laurent Dussopt and Gabriel M. Rebeiz

***Abstract*—The design and measurement of a push-push voltage controlled oscillator (VCO) at 18.66–18.3 GHz are presented in this paper. The circuit includes two packaged silicon transistors (Siemens BFP 540F) and a microstrip resonator tuned by two GaAs varactor diodes (M/A-COM ML46580). A 360-MHz tuning range is obtained with an output power of 0–3.1 dBm. The fundamental rejection is around 17 dB for a wide range of collector bias current. The phase noise is below −103 dBc/Hz at 100-kHz offset and below −122 dBc/Hz at 1 MHz for the entire tuning bandwidth.**

***Index Terms*—Oscillator, phase noise, silicon, varactor, voltage controlled oscillator (VCO).**

I. Introduction

The increasing demand for C- to K-band communication systems has driven the search for low-cost and low phase noise voltage controlled oscillators (VCOs). The main requirements for the design of low phase noise oscillators are a high quality factor resonator and a low $1/f$ noise active device.

The $1/f$ 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. Besides, 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].

This paper presents an 18-GHz push-push VCO using two low-cost packaged silicon bipolar transistors as active devices and a tunable half-wave microstrip resonator. The oscillation frequency is tuned by two varactor diodes weakly coupled to the resonator [Fig. 1(a)] [5], providing a tuning range of 360 MHz at 18.66 GHz (2%) and very low phase noise performance.

II. Push-Push VCO Design

Fig. 1 shows the push-push VCO presented in this paper. The resonator is a 9-GHz half-wave microstrip resonator on a 15 mils RT/Duroid (Rogers) substrate ($\varepsilon_r = 2.2$). The resonant frequency is tuned by two GaAs beam-lead varactor diodes M/A-COM ML46580, providing a capacitance of 173–480 fF and a series resistance of $4 - 6.2\ \Omega$ for a varactor bias $V_T = 18 - 6$ V. Two varactors are necessary in order to keep the circuit symmetric for proper operation of the push-push oscillator. A similar resonator has been presented previously [6] and has shown an excellent unloaded Q of 170 without varactor loading. It was also shown that the varactor loading had a small detrimental effect on the quality factor for high varactor bias (6–18 V) with a 2–3-dB increase of the phase noise level at 100-kHz offset in a regular 9-GHz VCO configuration [6]. This is due to the weak coupling between the resonator and the varactors provided by a 100 μm-gap interdigitated capacitor. The design of the tunable resonator was performed with Agilent-Momentum and ADS circuit simulator and has shown a resonant frequency of 9.22-9 GHz for a varactor capacitance of 173–480 fF.

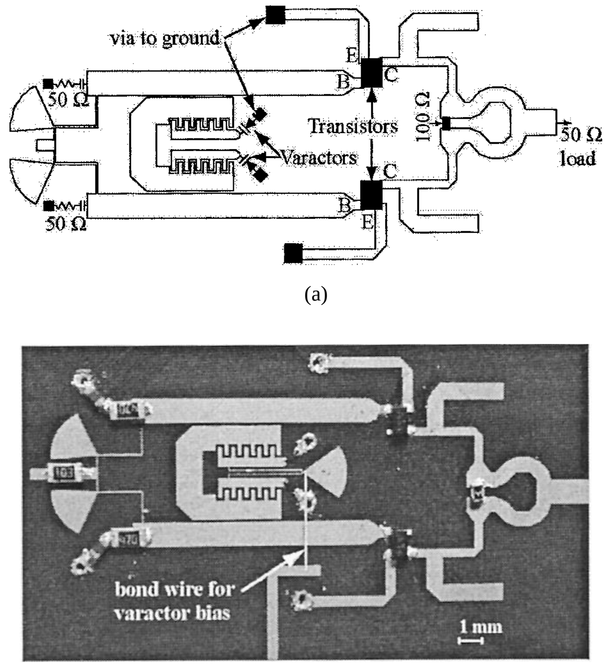

Fig. 1. (a) Layout and (b) photograph of the 18.66-GHz push-push VCO.

The S-parameters of the packaged transistor (Siemens BFP 540F) with a grounded emitter have been measured on the substrate using TRL calibration techniques, taking into account the packaging parasitics, the via-hole inductance to ground at the emitter, and the small delay lines at the base and collector ports. The measurements indicate a maximum available gain of 3.7 dB at 9 GHz ($V_{ce} = 2$ V, $I_c = 25$ mA, $|S_{11}| = 0.38$, $|S_{21}| = 1.53$, $|S_{12}| = 0.33$, $|S_{22}| = 0.09$).

A push-push oscillator is usually considered as two coupled oscillators working out of phase at a frequency f_0. A 180° coupling is provided by the resonator ensuring out of phase operation. The output signals of both oscillators are added through

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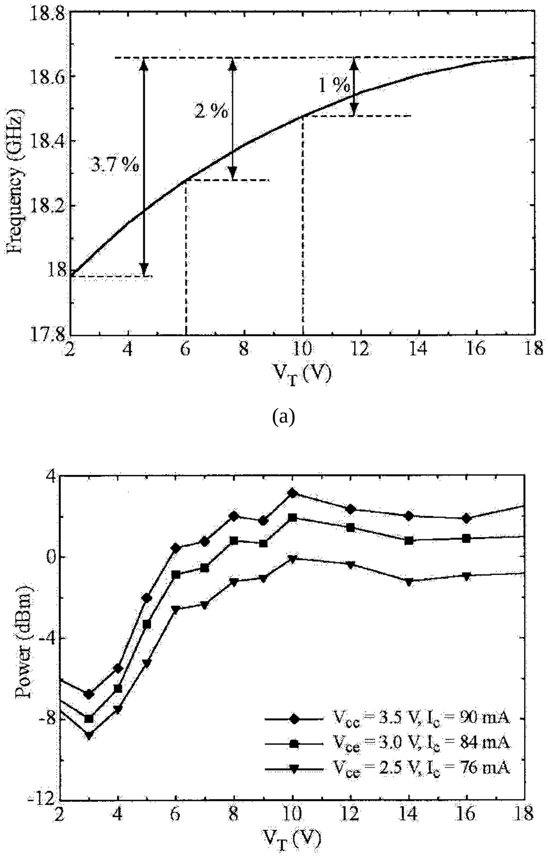

(b)

Fig. 2. (a) Measured oscillation frequency and (b) output power versus varactor bias for several collector currents.

a Wilkinson power combiner so that the fundamental (f_0) and odd harmonics $(3f_0, 5f_0, \ldots)$ cancel out while even harmonics $(2f_0, 4f_0, \ldots)$ add in phase, resulting in a $2f_0$ output signal.

The oscillator is designed with the method outlined in [6] with Agilent-ADS. A nonlinear Gummel-Poon BJT model of the transistor was extracted from the S-parameter measurements mentioned previously along with the dc characteristics of the device. The short-circuited t-lines at the emitter are then 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 VCO is shown in Fig. 1(b) and its total area is 24.7×12.1 mm^2.

III. Results and Discussion

Fig. 2 shows the output frequency and the output power versus varactor bias. The frequency tuning is 17.98–18.66 GHz for $V_T = 2 - 18$ V. This represents a maximum tuning range of 3.7%. The tuning range is reduced to 2% for a minimum bias of $V_T = 6$ V. Indeed, Fig. 2(b) shows that the output power is somewhat stable for $V_T > 6$ V and decreases drastically for low bias due to excessive loading of the resonator by the varactors. Table I summarizes the output power and dc-RF efficiency values. The collector current indicated is the total current for both transistors. Fig. 3 shows the power of the fundamental and first three harmonics versus collector current for $V_{ce} = 3$ V. The fundamental rejection is 16.5–17.7 dB for $I_c = 70 - 90$ mA and is not as good as the results presented in [6] for a fixed-frequency push-push oscillator. This is attributed to the asymmetry of the circuit due to fabrication errors, transistors discrepancy and varactors discrepancy. Still, a 17-dB rejection is acceptable and could be easily improved with an output filter.

The phase noise was measured with the HP 85671A phase noise utility on a HP 8564E spectrum analyzer. The varactor bias was provided by a set of batteries in order to avoid any low frequency noise upconversion. The phase noise is -103 to -107.7 dBc/Hz at 100-kHz offset and lower than -122 dBc/Hz at 1 MHz. This compares well with the results obtained with a similar fixed-frequency push-push oscillator (Table II) [6]. The measurements above 1-MHz offset were limited by the noise floor of our measurement set-up, which was roughly

TABLE I
Output Power and DC-RF Efficiency at 18 GHz for Several Transistor Bias

Transistor Bias (V, mA)	Output Power (V_T = 6-18 V) (dBm)	DC-RF Efficiency (%)
V_{ce} = 2.5, I_c = 76	-2.6 – 0	0.29 – 0.53
V_{ce} = 3.0, I_c = 84	-0.9 – +1.9	0.32 – 0.61
V_{ce} = 3.5, I_c = 90	+0.4 – +3.1	0.35 – 0.65

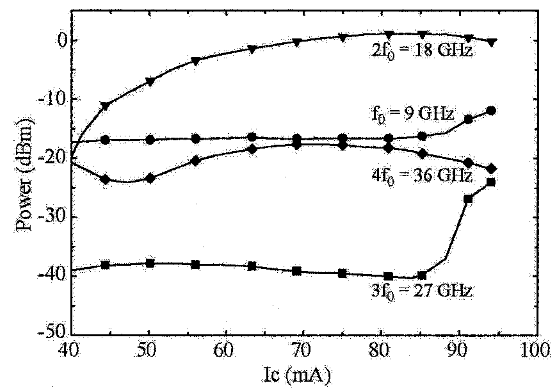

Fig. 3. Measured output power versus collector current of the push-push VCO at fundamental and harmonic frequencies ($V_{cc} = 3$ V).

TABLE II
Phase Noise Measurements of the Push-Push VCO Compared to a Similar Fixed-Frequency Push-Push Oscillator

Varactor Bias V_T (V)	Osc. Frequency (GHz)	Phase Noise Level (dBc/Hz)	
		100 kHz Offset	1 MHz Offset
6	18.30	-103	< -122
10	18.47	-104.7	< -122
18	18.66	-107.7	< -123
Push-Push Osc. [6]		-108	< -124

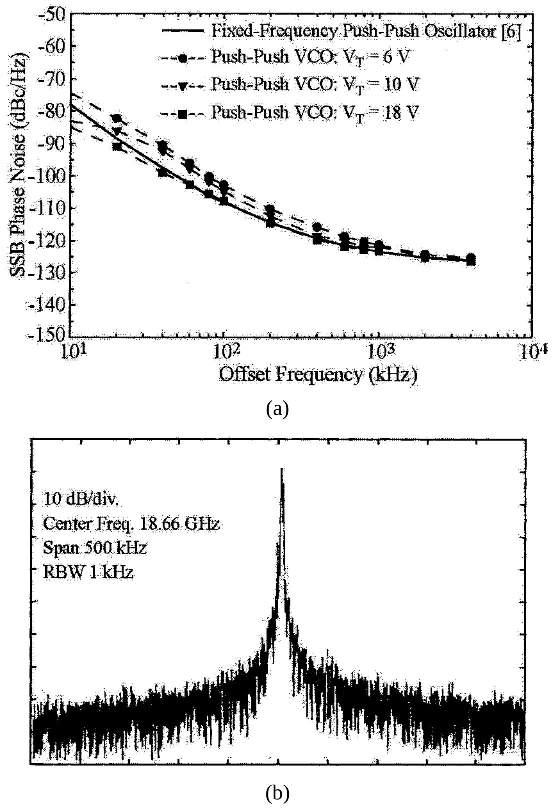

Fig. 4. (a) Phase noise measurements of the push-push VCO for different varactor bias (V_T) and a fixed-frequency push-push oscillator [6] and (b) output spectrum of the push-push VCO.

-128 dBc/Hz. The output spectrum at 18.66 GHz is shown in Fig. 4(b).

IV. Conclusion

This paper presents an 18-GHz push-push VCO including a tunable microstrip resonator and low-cost packaged silicon transistors as active devices. The resonator tuning elements are two GaAs beam-lead varactor diodes. This circuit demonstrated a 2% (360 MHz) frequency tuning with a maximum output power of 3.13 dBm and a phase noise lower than -103 dBc/Hz at 100 kHz from the carrier.

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