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2.4-GHz VCO DESIGN WITH COMPENSATION OF PROCESS VARIATIONS

E. KURJATA-PFITZNER

Institute of Electron Technology, al. Lotników 32/46, 02-668 Warszawa, Poland

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ABSTRACT

This work presents voltage controlled oscillator (VCO) design intended for integrated transceiver of Bluetooth standard communication system, in which full compensation of process parameters variations can be obtained. This is realized by fitting on chip capacitance of LC resonator in. This capacitance consists of two independent parts - first is used for coarse tuning of resonant frequency and the second is used for tuning inside the band 2.4 GHz.

1. Introduction

The process parameters variations of semiconductor devices are immanent feature of integrated circuit realization technique. Integrated circuit designing takes it into consideration by using limit of device model parameters (minimal, maximal, typical or others) extracted by foundry. This parameter sets are the base of corner analyses that give the area of possible magnitudes of designed circuit parameters. Designing of analogue circuit using typical model parameters only is invalid from the production yield point of view.

High frequency oscillators belong to the integrated circuits, which parameters depend very strongly on process variations. Therefore all circuit parameters (frequency, amplitude of output signal, current consumption, phase noise) may be different for each run and no oscillation may occur also. To illustrate this problem corner analysis of VCO designed using typical parameters for 2.44 GHz was performed. Obtained results show that in a real circuit the oscillation frequency may be in the range 2.2 – 2.7 GHz (Fig. 1a) with various amplitudes (Fig. 1b). No oscillation is possible also (Fig. 1a, b).

Publications concerning VCO do not deal with the problem of the effects of process variations, beside information that tuning circuit covers changes resulting from process and temperature variations [1, 2]. It is possible when oscillator's voltage gain $K = \mathrm{d}\boldsymbol{f}(V)/\mathrm{d}V$ (where V is the control voltage) is large enough – about few hundreds MHz/V. Such solution is not advisable for Bluetooth application, because K should be about 85 MHz/V and phase noise becomes greater

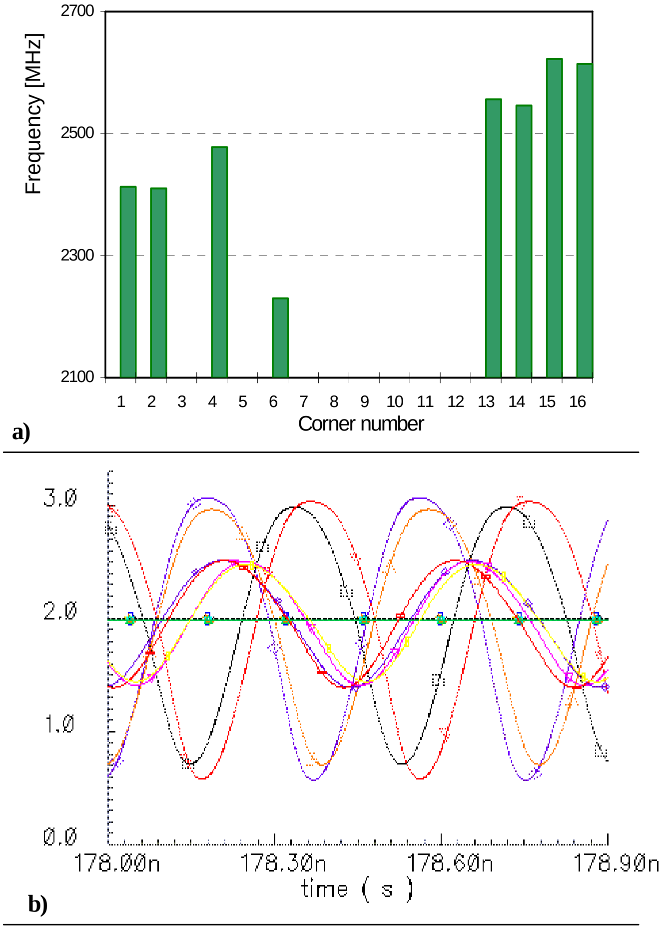

Fig. 1. Results of corner analysis of VCO that for typical parameters oscillates at 2.44 GHz: a) oscillation frequency, b) waveforms

when gain is larger. For this reason integrated high frequency oscillators are initially trimmed using external elements [3].

In this paper design of LC oscillator, which satisfies requirements of Bluetooth standard and produces oscillation frequency independently of process variations is presented. Advantage of the proposed solution is that initial frequency tuning is made by the change of resonant capacitance fully placed on chip and no external elements are needed. Voltage dependent resonant capacitance consists of two parts, which are controlled separately. First part is for coarse tuning and the second for tuning inside the desired band.

2. VCO with two step frequency tuning

The purpose of this work was to design VCO intended for integrated transceiver of Bluetooth standard without external elements for initial frequency trimming, which is necessary because of process variations.

BiCMOS SiGe process featured of bipolar transistor f_T >35 GHz was chosen to implement of VCO because it is adequate to meet requirements of Bluetooth transceiver.

Design was performed choosing topology of cross coupled differential pair [4–6] which allows to obtain a wide tuning range and is appropriate to minimalization of phase noise. Moreover such configuration decreases amplification of noise propagated via substrate and supply rails and its conversion to higher frequency.

Differential pair is composed of bipolar SiGe npn transistors and makes with resonator a negative resistance (Fig. 2). Resonator consists of inductance L and voltage dependent capacitance $C(V)$. Resonator capacitance is made of three independent capacitances: constant capacitance C_o and two voltage regulated capacitances $C_t(V_t)$ and $C_c(V_c)$. They are implemented as reverse biased collector-base junctions.

Constant capacitance C_o is used to linearisation of voltage controlled capacitances. The best linearisation may be achieved when C_o is comparable with C_c + C_t, but then the range of resultant $C(V)$ tuning is too small to assure the oscillation over process variations. To achieve wide enough tuning range C_o is greater but it leads to small non-linearity of voltage gain of the designed VCO.

Inductance is implemented on chip using metal 1 and short-circuited metal 2 layers as rectangular spiral coil. Simulation model of it is included inside foundry design kit and therefore parameters of other circuit elements were fit to it in.

Capacitances, which couple bases and collectors of differential pair, are used to decrease the base bias below DC bias of collectors. It allows growing the collector voltage to required level without entering saturation region of transistor what is useful to phase noise reduction.

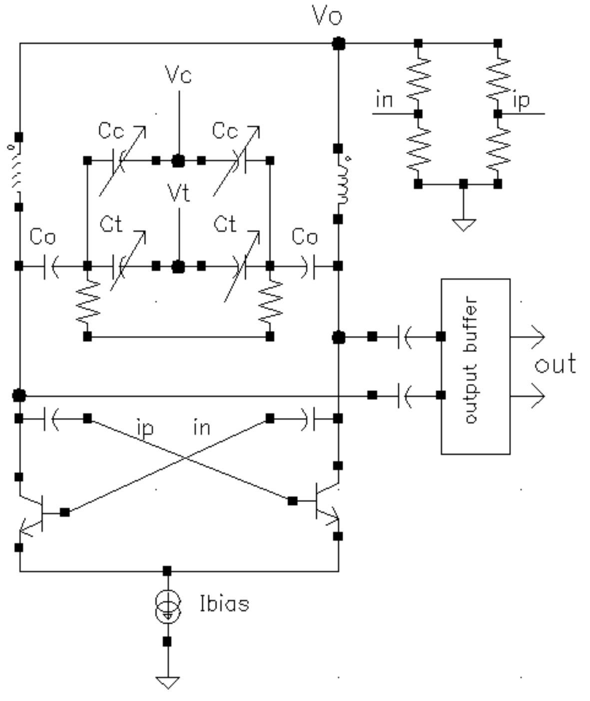

Fig. 2. VCO topology

Output buffer is capacitive coupled to the oscillator output.

The idea of frequency regulation relies on applying of parallel-connected capacitances C_c and C_t that are voltage controlled separately. First of them C_c is used to coarse tuning (trimming) which compensates process variations and the second C_t is used to fine frequency tuning inside Bluetooth band with appropriate voltage gain.

The coarse frequency tuning adapts resonator capacitance to real parameters of chip devices and is made by change of voltage V_c controlling capacitance C_c. For V_t = 1.35 V (middle of the V_t range) V_c should be chosen in such a way that oscillation frequency should be close to the middle of the band = 2.44 GHz. This type of coarse tuning seems to be more profitable in comparison to the method of capacitances turn on or off using switches [4], because they make additional phase noise sources. Capacitance C_t controlled by V_t voltage is used for fine-tuning according to required channel, usually in phase locked loop configuration circuit, which is a part of frequency synthesizer.

Bias current determines oscillation amplitude of VCO and is defined by current source (Fig. 2) designed as bipolar current mirror. Bias current cannot be too great in order to eliminate the work of transistors inside saturation region. On the other hand it cannot be too small because noise to signal ratio should be as small as possible. It was stated that bias current of 5 mA is accurate to obtain 1 V amplitude at the oscillator output.

3. Simulation results

Design of VCO was performed using *Cadence* design framework and design kit related to technology process SiGe (AMS). It contains extracted by foundry model parameters of all semiconductor devices for limit technology process variations. All simulations were done with *SpectreRF*.

Figure 3 shows dependence of oscillation frequency on tuning voltage V_t for all combinations of device model parameters (corner analysis). These plots were calculated for suitable chosen voltage V_c in such a way that oscillations of 1 V amplitude occur in the required band. The values of V_c voltage are different for each bipolar transistor parameter set.

It appears from corner analysis that oscillations occur in the interval 2.40 – 2.48 GHz for each parameter set. But the range of control voltage V_t is different for various bipolar transistor parameter set. For typical parameter set (*tm*) V_t is in the range from 0.7 V to 1.7 V and for parameter set called (*hs*) V_t is in the range 0. 1 – 0.7 V (Fig. 3).

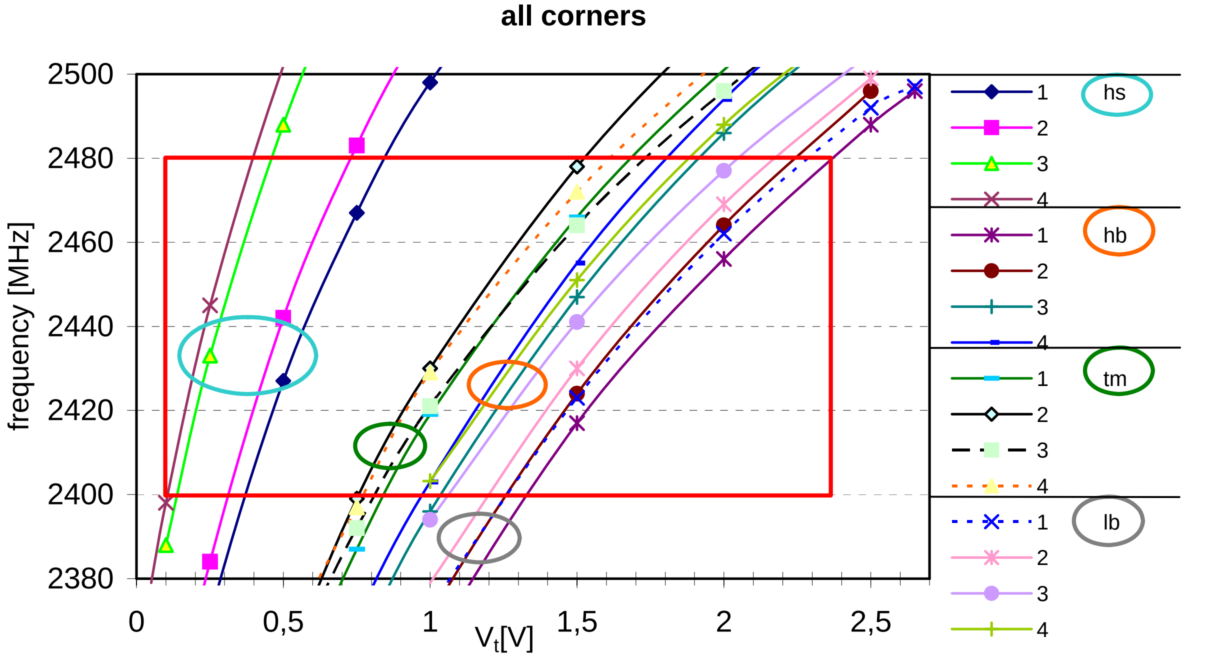

Fig. 3. VCO characteristics for four parameter sets of SiGe transistor model: *hs*, *tm*, *hb*, *lb* for two extreeme values of resistance and capacitance. Red frame denotes area of oscillator tuning inside Bluetooth band.

VCO's voltage gain takes desired, for Bluetooth application, value of K = 85 MHz/V for typical bipolar parameters. But the corner analysis leads to the conclusion that voltage gain of VCO is process dependent and may vary from 260 MHz/V for bipolar transistors modeled by parameter set called *hs* to 77 MHz/V for parameter set called *lb* (the mean value was calculated taking the straight line as an approximation of $\boldsymbol{f}(V_t)$).

The main noise sources in the VCO are bipolar transistors of differential pair and variations of their process parameters effects significantly on phase noise of the circuit. The PSS (Periodic Steady State) noise analysis was performed for all four (given by foundry) bipolar transistor parameter set and typical values of other circuit elements in the case of carrier frequency in the middle of the Bluetooth band 2.44 GHz (Fig. 4). It leads to the conclusion that noise parameters of VCO are process sensitive. The most significant phase noise is for *hs* parameter set of npn transistors: at 3 MHz offset is equal –118.5 dBc/Hz

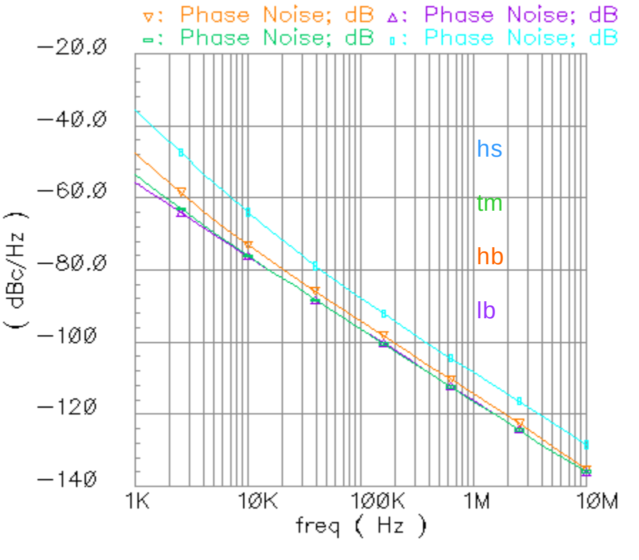

Fig. 4. Phase noise for carrier frequency 2.44 GHz and four parameters sets of bipolar transistor model (*hs*, *tm*, *hb*, *lb*). Resistances and capacitances are typical.

and the smallest one is –126 dBc/Hz for *lb* parameter set at the same offset .

Results of PSS noise analysis performed for typical parameter set of bipolar transistor and combination of extreme limit values of resistance and capacitance confirm their meaningless influence on phase noise in comparison with effect of bipolar transistor parameter variations (Fig. 5). Designed VCO is characterized by phase noise from –123 dBc/Hz and – 126 dBc/Hz depending on model parameter values of resistance and capacitance in the case of 3 MHz offset.

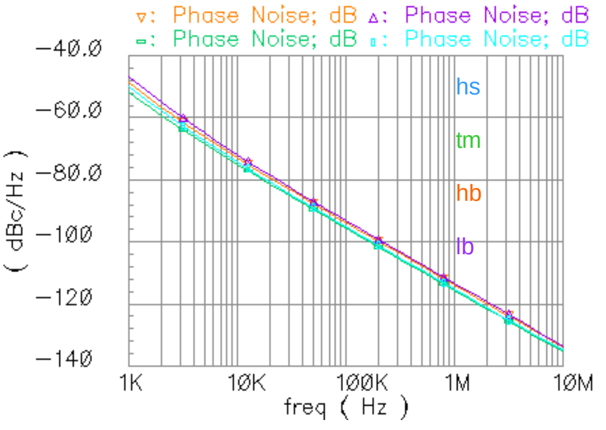

Fig. 5. Phase noise for carrier frequency 2.44 GHz and extreme values of resistance and capacitance in the case of typical bipolar transistor parameters.

Table 1. VCO phase noise inside 2.4 GHz band

Carrier frequency	Tuned voltage	Phase noise [dBc/Hz]		
f [MHz]	V_t [V]	Offset		
		1 KHz	100 KHz	3 MHz
2398	0.9	–47.68	–94.17	–124.1
2455	1.5	–47.60	–94.15	–124.1
2483	1.95	–47.34	–94.02	–124.1

Table 1 contains values of phase noise for typical parameters of all circuit devices for three frequencies: inside and close to Bluetooth band. One can see that in the range 2.40 – 2.48 GHz phase noise is practically independent on carrier frequency.

4. Conclusions

VCO design presented in this work is characterized by frequency tuning in two independent steps which are performed by voltage control of on chip capacitances. First of them is used for course tuning and the second for fine-tuning inside 2.4 GHz band. It allows obtaining voltage-controlled oscillations for each run of technology process.

The parameters of the designed VCO allow implementing it in transceiver of Bluetooth standard communication system because the voltage gain takes desired value and phase noise is less than –120 dBc/Hz at 3 MHz offset for the best part of process parameters. Moreover phase noise is practically independent on frequency inside the band.

Presented design was aimed for BiCMOS SiGe process (AMS) but the use of two independently controlled on chip capacitances inside differential pair for frequency tuning of VCO may be implemented in other processes and frequency ranges also.

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