4. CONCLUSION

A patch antenna capable of generating a wide horizontal radiation pattern covering about one half-space has been proposed. The broadening of the antenna's horizontal radiation pattern is easily achieved by using a narrow radiating patch that incorporates an inverted-V ground plane. Prototypes showing a wide horizontal radiation pattern for WLAN operation in the 2.4-GHz band have been successfully implemented. The results obtained indicate that the bend angle of the inverted-V ground plane has a highly significant effect on the broadening of the horizontal radiation pattern of the proposed antenna.

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LOW-PHASE-NOISE CMOS VCO WITH HARMONICALLY TUNED LC TANK

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Received 22 December 2003

ABSTRACT: *A low-phase-noise voltage-controlled oscillator (VCO) has been demonstrated using a harmonically tuned LC resonance tank. In this circuit configuration, the voltage shape at the differential cell is almost rectangular; thus, the cell is switched effectively and the phase noise is reduced. More importantly, the proposed tank suppresses down-conversion of the noise around* $2f_0$ *to the phase noise, due to the* 2^{nd} *harmonic short of the tank. Therefore, the phase noise of the VCO based on the tank is improved considerably. The VCO for 1-GHz operation has been realized using a 0.35-μm CMOS process. It shows a phase noise of −111.6 dBc/Hz at 100 KHz offset, which is a 5.7-dB improvement over a comparable standard VCO.* © 2004 Wiley Periodicals, Inc. Microwave Opt Technol Lett 42: 164–167, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20240

Key words: *CMOS; VCO; Harmonic tuned LC tank; low phase noise*

INTRODUCTION

Recently, the phase noise of LC voltage-controlled oscillators (VCOs) has been a popular issue for CMOS RF researchers because it remains in a key problem area for the realization of a single-chip CMOS radio [1]. The high noise is due to the poor quality factor of passive components in the CMOS process and the inferior $1/f$ noise characteristic of MOSFET. Many attempts have been made to reduce the phase noise of the oscillators [2–4]. Despite these endeavors, the optimum design for LC oscillators is still pending. The rule of thumb for a low-phase-noise LC oscillator design is to choose the largest inductor in a given process. The capacitor is automatically determined by the relation given for resonance, $f = 1/2\pi\sqrt{LC}$ [5]. On the other hand, a recent paper asserts that there is an optimum value of inductance for a low-phase-noise VCO related to the overall circuit constraints [6]. Also, it is demonstrated that the phase noise can be reduced using other circuit techniques, such as filtering of current source noise at $1/f$ region or $2f_0$ [7, 8].

In this paper, we propose a new VCO using a harmonically tuned LC tank for the reduced phase noise. It is well known that the noise from a Gilbert cell can be minimized by employing a fast rising voltage at the zero crossing point [9]. To realize this concept, we have employed a harmonically tuned LC tank, which can deliver a square waveform voltage to the cell. The proposed LC tank is open at the fundamental frequency and 3rd harmonic, and is short at the 2nd harmonic. The shortness at $2f_0$ stabilizes the tail point bias and reduces down-conversion of the noises at the frequency to the phase noise. Therefore, the VCO based on the tank can deliver an improved phase-noise performance. The CMOS VCO for 1-GHz operation shows a phase noise of −111 dBc/Hz at 100-KHz offset, which is a 5.7-dB improvement over a comparable standard LC VCO.

FUNDAMENTALS OF LC OSCILLATOR PHASE NOISE

The well-known phase-noise model for an oscillator is Leeson's proportionality [10]:

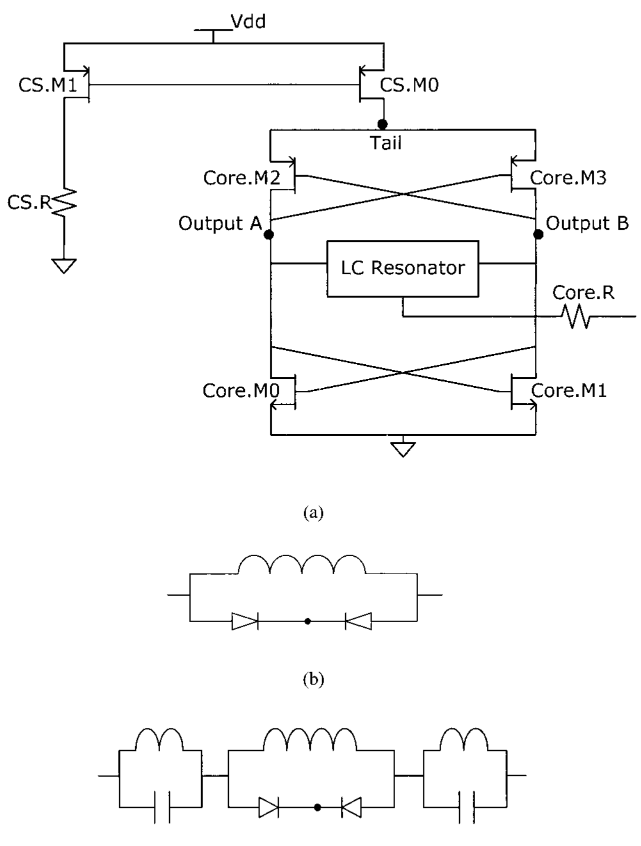
$$L(\omega_m) \propto \frac{1}{V_O^2}\cdot\frac{kT}{C}\cdot\left(\frac{\omega_O}{Q}\right)^2\cdot\frac{1}{\omega_m^2}, \qquad (1)$$

where the phase noise is given by the kT/C noise, which is shaped in the frequency domain by the LC tank and normalized to the power in the tank. The phase noise is scaled by a specific noise factor F, which needs to be identified experimentally. Recently, Rael et al. [9] extracted the F value of an LC oscillator from the noise model of mixers with a switched differential pair [11]. The noise factor is given by

$$F = 2 + \frac{8\gamma IR}{\pi V_o} + \gamma\frac{8}{9}g_{mbias}R, \qquad (2)$$

where I is the bias current, γ is the channel noise coefficient of the FET, V_o is the voltage across the resonator, which represents the slope of voltage waveform at zero crossing, R is the load resistance, and g_{mbias} is the transconductance of the current-source FET. Eq. (2) describes the phase-noise contributions from three noise sources: tank resistance, differential-pair FETs, and current source. The noise sources from the above three parts are frequency-translated into the phase noise by the nonlinear effects of the active components.

In typical oscillators operating at high current levels with moderate-to-high resonator quality factors, the current-source contribution is very important and the contribution can be reduced



(a)

(b)

(c)

Figure 1 Prototype LC VCOs: (a) designed LC VCO topology; (b) standard LC tank; (c) harmonically tuned LC tank

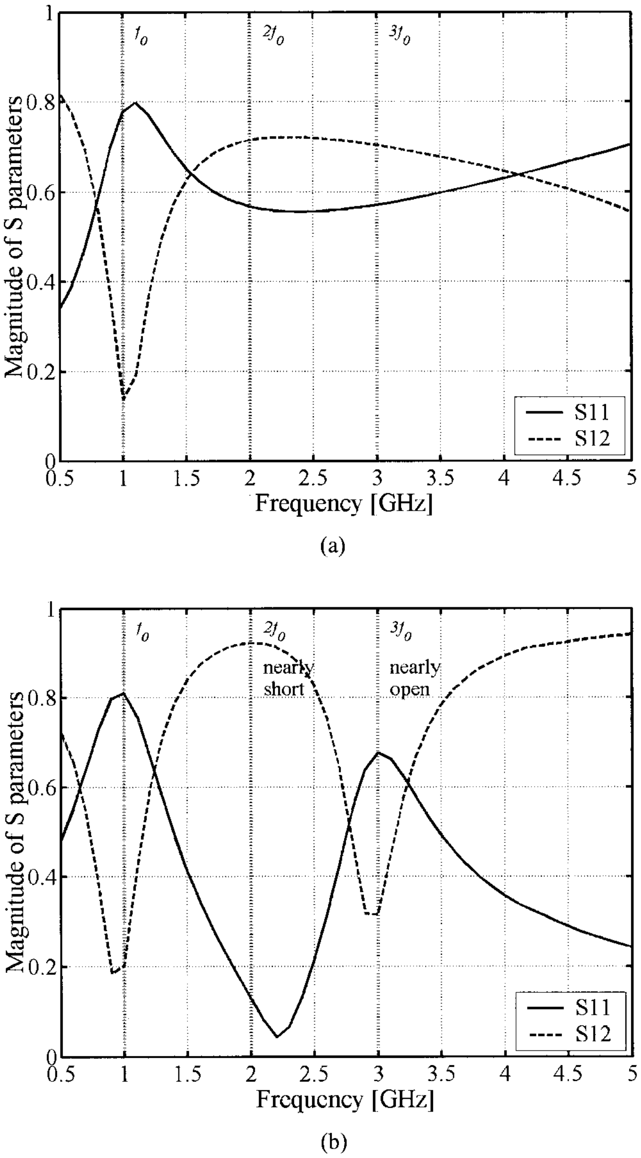
using filtering technique [7, 8]. In our VCO, the noises from the current source and tank resistors are suppressed by the proposed LC tank because the shortness at $2f_0$ filters the noise components at the frequency. Therefore, the tank stabilizes the tail-voltage fluctuation and reduces the down-conversion of the noise components at $2f_0$ into the phase noise. The phase-noise generation from the differential pair, described by the second term in Eq. (2), can be minimized by maximizing V_0, which is proportional to the slope at zero crossing [11]. To maximize the slope at zero crossing, a square waveform voltage is created at the tank using the harmonically tuned LC resonator. The experimental result and its analysis confirm the excellence of the proposed LC VCO.

DESIGN OF THE HARMONICALLY TUNED OSCILLATOR

The harmonically tuned LC VCO is implemented in a 0.35-μm CMOS process by ST Microelectronics. As shown in Figure 1, complementary cross-coupled FETs are used for better phase-noise performance [12, 13]. PMOS current sources are chosen due to their good flicker-noise characteristics. We have designed two types of VCOs—standard and harmonically tuned—which are in exactly the same condition, with the exception of the resonators. For the harmonic tuning, the tank should be open-circuited at the fundamental frequency and odd harmonics, and short-circuited at the even harmonics. But we have simplified the circuit to the 3rd harmonic tuning by using a series connection of two resonance LC tanks, one with resonance at f_0 and the other at $3f_0$, and the combined one is short-circuited at $2f_0$. The calculated values of the inductors and capacitors should be further optimized because of the parasitic components of the cross-coupled transistors, such as C_{gs} and C_{gd}. Figure 2 displays the simulated S-parameters of the two tanks for 50Ω terminations. Both figures show similar behaviors around f_0. However, the differences obviously appear due to the short circuit at $2f_0$ and the open circuit at $3f_0$.

MEASURED RESULTS AND DISCUSSION

The post-simulated center frequencies of the VCOs are 990 and 981 MHz, respectively. Both VCOs have more than 20% tuning ranges and their current consumption in the core is 5.4 mA from the 2.9-V supply. They show very similar DC and RF behaviors (except the phase-noise performance) because of the same topologies (except the LC tanks). A photograph of the two VCOs is given in Figure 3. The size of standard VCO is 460 × 700 μm^2 and that of the proposed VCO is 620 × 880 μm^2. Phase-noise simulation using CADENCE SpectreRF shows that the proposed VCO is superior to the standard one. The simulated spectra do not appear in this paper because they almost coincide with the measurement results given in Figure 4. The phase noises at 100-KHz offset are



(a)

(b)

Figure 2 S-parameters of the (a) standard LC tank and (b) harmonically tuned LC tank

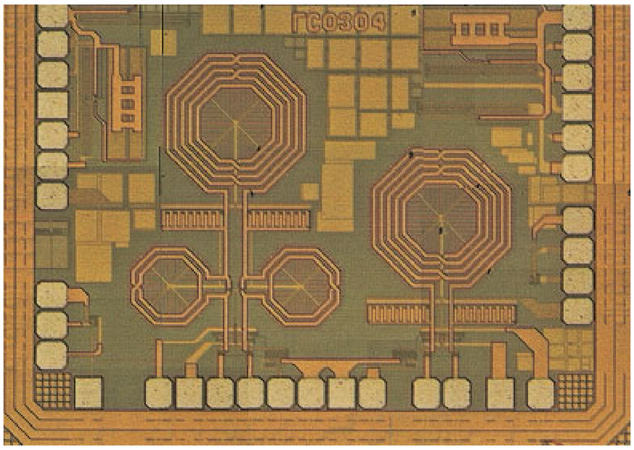
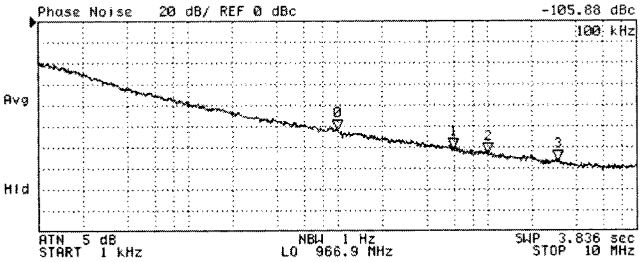


Figure 3 Photograph of the prototype VCOs. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

−105.88 dBc and −111.6 dBc, respectively, thus a 5.7-dB improvement is exhibited by the harmonically tuned tank.

Figure 5 shows the simulated voltage waveform at the tail and output nodes of the Gilbert cell [see Fig. 1(a)] with a sinusoidal voltage wave for the standard LC VCO and a squarelike wave for the harmonically tuned LC VCO, which obviously provides a steeper zero crossing than the former, by 2.2 times in this case. The tail-node voltage of the proposed VCO has far less fluctuation than that of the standard one. This means that the harmonically tuned LC tank filters out the noise at the 2^{nd} harmonic frequency by the short circuit and suppresses the phase noise, similarly to the passive filters at the tail point [7, 8].



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N      SWP PARAM        VAL

0        100 kHz     -105.88 dBc
1        600 kHz     -122.53 dBc
2          1 MHz     -127.27 dBc
3          3 MHz     -134.97 dBc
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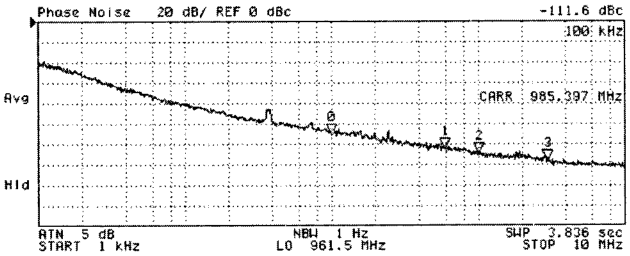
(a)



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N      SWP PARAM        VAL

0        100 kHz      -111.6 dBc
1        600 kHz     -125.81 dBc
2          1 MHz     -130.77 dBc
3          3 MHz     -136.71 dBc
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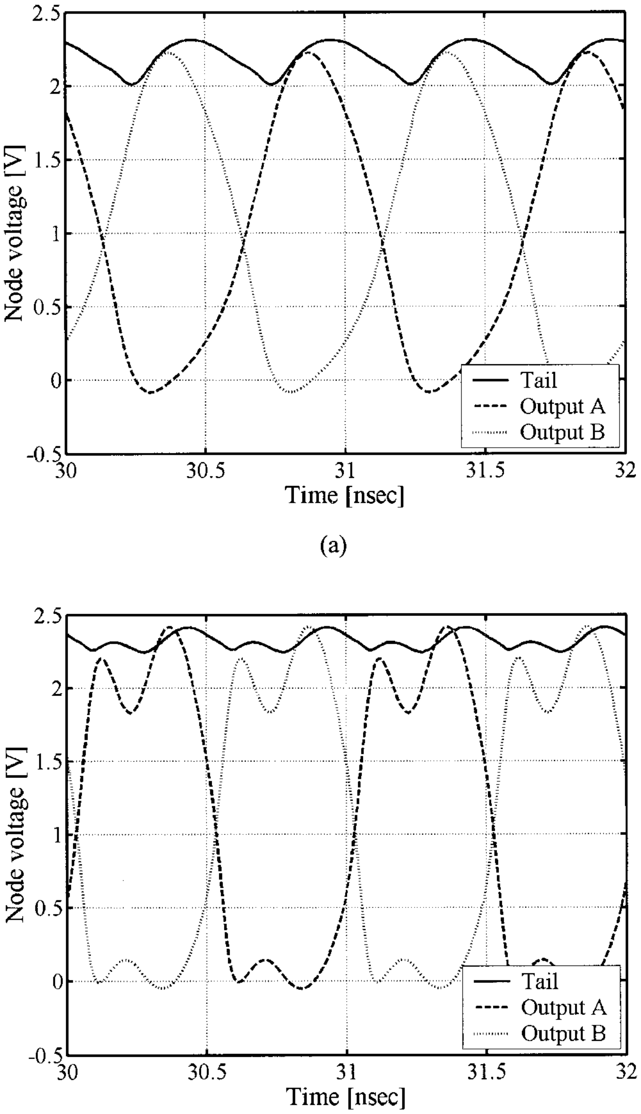
(b)

Figure 4 Measured phase-noise spectra of (a) standard VCO and (b) harmonically tuned VCO



(b)

Figure 5 Simulated time-domain voltage waveforms of (a) standard VCO and (b) harmonically tuned VCO

The noise contributions at 100-KHz offset frequency, analyzed from the various noise sources, are summarized in Table 1. The noise sources are depicted in Figure 1 and the core resistor *R* is the resistor through which the control voltage for a varactor is injected. The dominant 10 contributors are listed in descending order. The data are expressed as spot noise in V^2/Hz and can be calculated to the output phase noise when normalized to the signal power. They clearly show that the proposed harmonically tuned tank reduces the phase noise from all sources. The noises from the current sources and core resistor are suppressed by more than 10 dB and the noises from the Gilbert cell are reduced by a lesser amount. Therefore, we can conclude that the main effect for the reduced phase noise is a filtering of noises at $2f_0$ by the short circuit at the frequency and that the sharper switching of the Gilbert cell is a secondary effect. For our VCO, the core resistor is the largest noise

TABLE 1 Phase-Noise Contributors of the Prototype LC VCOs

Standard LC VCO			Harmonically Tuned LC VCO		
Noise Sources	Noise Contribution (V^2/Hz)	% of Total	Noise Sources	Noise Contribution (V^2/Hz)	% of Total
Core.R	1.63e-13	52.15	Core.R	1.23e-14	17.55
CS.M0, thermal	2.22-14	7.13	Core.M1, thermal	9.89e-15	14.16
CS.M1, thermal	1.82e-14	5.84	Core.M0, thermal	9.87e-15	14.13
CS.M1, flicker	1.27e-14	4.06	Core.M2, thermal	8.04e-15	11.51
Core.M1, thermal	1.25e-14	4.02	Core.M3, thermal	8.00e-15	11.45
Core.M0, thermal	1.25e-14	4.02	Core.M1, flicker	2.52e-15	3.61
Core.M2, thermal	1.01e-14	3.24	Core.M0, flicker	2.42e-15	3.47
Core.M3, thermal	1.01e-14	3.24	CS.M0, thermal	2.05e-15	2.94
Core.M1, flicker	9.44e-15	3.02	CS.M1, thermal	1.77e-15	2.53
Core.M0, flicker	9.32e-15	2.99	Core.M3, flicker	1.66e-15	2.37

source and the percentage of the resistor noise to the total output noise decreases from 52.2% to 17.6% by the harmonically tuned tank.

CONCLUSION

A low-phase-noise VCO using a harmonically tuned LC tank has been proposed and demonstrated. The tank is realized using two series-connected LC tanks, with resonances at the fundamental and 3^{rd}-harmonic frequencies. The combined circuit of the tanks provides a short at the 2^{nd} harmonic. The tank causes the voltage waveform across from it to be nearly rectangular in shape, and the slope at zero crossing of Gilbert cell becomes steeper than that of the standard LC VCO. The steeper voltage reduces the generation of the 2^{nd}-harmonic noise component and improves the phase noise. More importantly, the tank characteristic, short at $2f_0$, significantly suppresses the down-conversion of various noise sources at the 2^{nd}-harmonic frequency into the phase noise. Prototype VCOs with the harmonic tuning tank and standard tank are implemented for 1-GHz operation using the 0.35-μm CMOS process by ST Microelectronics. The VCO with the harmonically tuned tank delivers a phase noise of -111.6 dBc at 100-KHz offset, which is a 5.7-dB improvement over the VCO with the standard LC tank.

ACKNOWLEDGMENTS

This work was supported in part by the Brain Korea 21 Project of the Ministry of Education. The authors would like to thank Kwangjun Youn, Jeong-Cheol Lee, and Joonsuk Lee at Future Communication IC, Inc. for their assistance with the chip fabrication.

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EVALUATION OF DIRECTIVITY AND GAIN FOR TIME-MODULATED LINEAR ANTENNA ARRAYS

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Received 20 December 2003

ABSTRACT: *In this paper, the directivity and gain of several types of time-modulated linear antenna arrays are obtained. Three types of array elements are considered: arrays with isotropic elements, parallel short dipoles, and collinear short dipoles. Curves of directivity as functions of inter-element spacing and sidelobe levels (SLLs) are presented. A comparison between the computed and measured gains of a time-modulated printed dipole linear array shows reasonable agreement.* © 2004 Wiley Periodicals, Inc. Microwave Opt Technol Lett 42: 167–171, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20241

Key words: *antenna arrays; time modulation; directivity*

1. INTRODUCTION

Time-modulated antenna arrays are attractive for the synthesis of low/ultra-low sidelobes [1–3]. As compared to conventional antenna arrays, time-modulated antenna arrays introduce an addi-