# Design of a 24-GHz CMOS VCO With an Asymmetric-Width Transformer

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***Abstract*—A K-band CMOS voltage-controlled oscillator (VCO) is implemented with a 0.18-$\mu$m radio frequency CMOS process. For low supply voltage operation, a transformer-feedback topology using a transformer is proposed. The analysis of the transformer-feedback VCO is presented. This shows that the inductance ratio of the transformer must be optimized, and asymmetric-width transformers allow the easy optimization and the high Q-factor. Based on this analysis, the transformer design consideration of the transformer feedback VCO is presented. The VCO operates at 24.27 GHz with the phase noise of −100.33 dBc/Hz at 1-MHz offset, and it consumes 7.8 mW from a 0.65-V supply voltage.**

***Index Terms*—Asymmetric-width transformer, low voltage, transformer feedback, voltage-controlled oscillators (VCOs).**

## I. Introduction

With the growing demands for circuitry with its low cost, low power consumption, high level of integration, and high data rates, RF CMOS circuits are now becoming important components in wireless systems over 20 GHz [1]–[4]. Particularly, the signal generation block becomes one of the most power consuming blocks [5], [6]. Also, the supply voltage reduction as a result of continuous device scaling degrades the phase noise performance by limiting oscillation amplitudes. Therefore, a voltage-controlled oscillator (VCO) over 20 GHz should also be implemented to have high signal purity with a reduced supply voltage.

To obtain a large oscillation amplitude with a reduced supply voltage, a novel drain-to-source transformer feedback topology using a transformer has been proposed [7]. As shown in Fig. 1, the physical dimensions of the conventional transformer such as width or thickness of each part of the transformer are the same. To get a proper impedance transform ratio, the primary or secondary part requires more than one turn [8]. For the applications over 20 GHz, the ohmic loss of a metal conductor appears more than expected and degrades the quality factor. In the VCO design, this results in a reduction of the oscillation amplitude and the worse phase noise [5]. These will be mentioned in more detail in Section II.

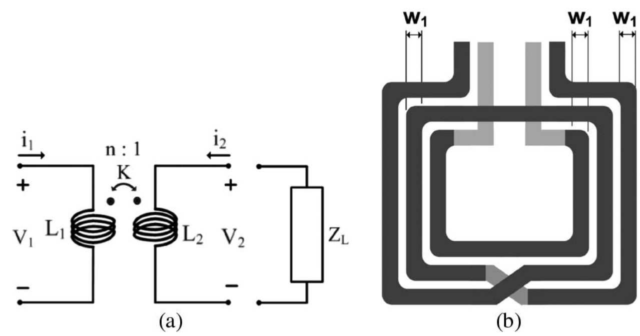


Fig. 1. Conventional transformer. (a) Equivalent circuits. (b) Layout.

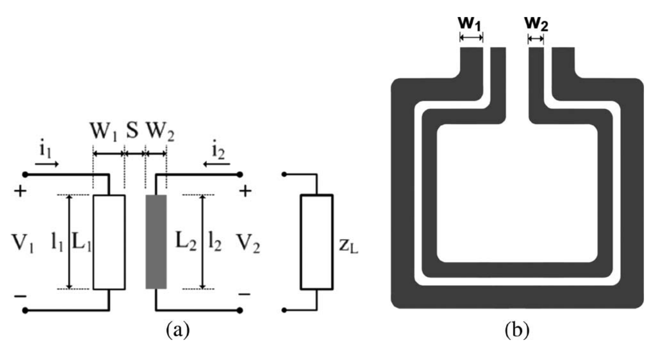


Fig. 2. Asymmetric-width transformer. (a) Equivalent circuits. (b) Layout.

In this brief, a modified drain-to-source transformer feedback VCO is implemented using an asymmetric-width transformer, which has a high quality factor. As shown in Fig. 2, the characteristics are determined by different physical dimensions of each part instead of the turn ratio [8]–[10].

In Section II, a conventional transformer and an asymmetric-width transformer are compared based on the layouts, and the low loss characteristic of the asymmetric-width transformer is demonstrated by simulation. The analysis of the transformer feedback VCO based on the small signal model and the design considerations of the VCO are presented in Section III. In Section IV, the measurement results of the fabricated 24-GHz VCO using a 0.18-$\mu$m RF CMOS process are presented. Section V concludes this brief.

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## II. High-Q Transformer With Asymmetric Width

The characteristics of a conventional transformer are decided by the turn ratio. A multiturn inductor is required in the primary or secondary part, as shown in Fig. 1. However, in the case of the asymmetric-width transformer, the characteristics of the transformer are determined by the physical dimensions of each part, including width, length, and thickness [8], [9]. Thus, only one single-turn line inductor is required, as shown in Fig. 2. The possible drawbacks caused by a multiturn transformer over 20 GHz are given below.

- Metal bending and metal crossing for the multiturn inductor cause an additional ohmic loss and degrade the quality factor of the inductor [11], [12].
- Capacitive coupling acts as a parasitic effect and causes signal losses. The closely located metals in the multiturn inductor, which have same-direction currents, will disturb the current flow through the surface of the metals that face each other. This effect, as well as skin effect, causes severe ohmic losses [8], [13]. However, an asymmetric-width transformer eliminates high-frequency loss because the capacitive coupling effect is absorbed into the characteristic impedance of the transformer [8], [9].
- The increased length of the primary metal due to more than one turn makes the inductance larger than required at higher frequencies. If the radius is reduced to have proper inductance, then the quality factor of the inductor is degraded [8], [11].
- In the viewpoint of VCO design, the large inductance of a conventional transformer limits the tank capacitance and the size of a transistor. The large capacitance of an LC tank can minimize the effect of the instantaneous voltage change by the injected noise current [6]. The instantaneous voltage change stands for a noise voltage, and it is one of the reasons of the VCO's phase noise. Thus, limited tank capacitance would degrade the phase noise performance. Also, the oscillation amplitude of the VCO in the current-limited regime is proportional to the bias current [11], and it has considerable effects on the phase noise performance [5]. In the drain-to-source feedback VCO without a current source for low supply voltage operation, the bias current is determined by the size of transistors of the cross-coupled pair. Thus, the small transistor limits not only the bias current but also the oscillation amplitude of the VCO. Consequently, the phase noise of the VCO is degraded.

To demonstrate the above characteristics, the quality factors of both transformers are simulated. The inductors that are used for the primary parts of both transformers are shown in Fig. 3. Fig. 3(a) shows the two-turn inductor, and Fig. 3(b) shows the single-turn inductor with the same inductance of 0.73 nH. The former is for a conventional transformer, and the latter is for an asymmetric-width transformer. For the same inductance, both inductors have different dimensions, and it is shown in Fig. 3. The quality factors of the above inductors and transformers are simulated using a 2.5D EM simulator and compared in Fig. 4. As shown in Fig. 4(a), the quality factor of a single-turn inductor is higher than that of a multiturn inductor. Also, as shown in Fig. 4(b), the same trend is obtained for transformers, as we expected.

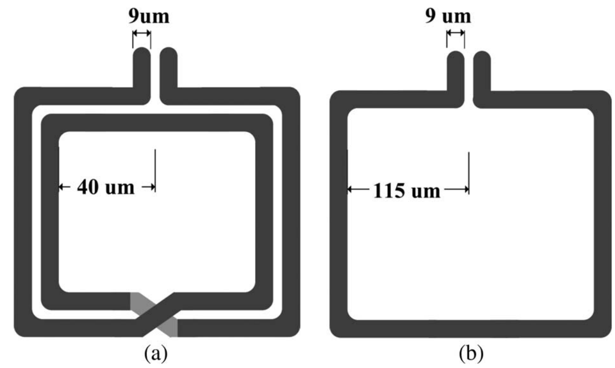


Fig. 3. Primary inductor of the transformer. (a) Two-turn inductor. (b) Single-turn inductor.

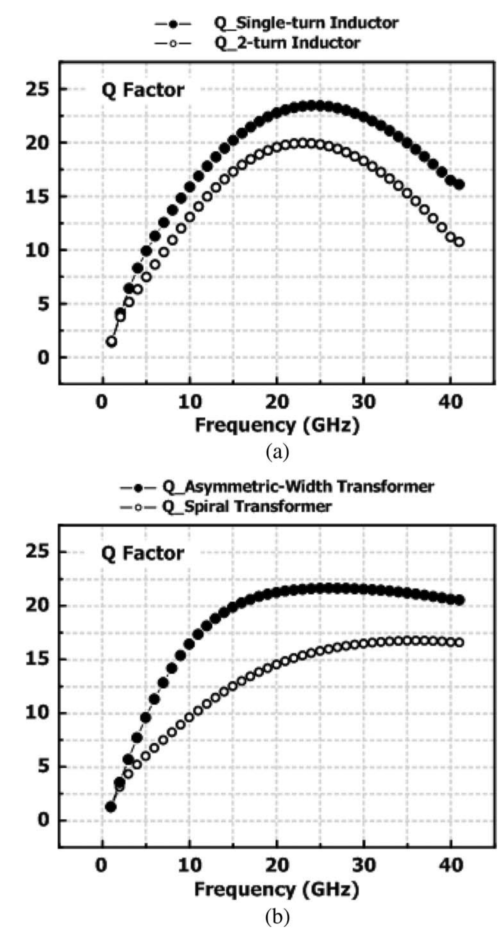


Fig. 4. Comparisons of the quality factors. (a) Inductors with same inductance of 0.73 nH. (b) Transformers with same primary inductance.

## III. Circuit Analysis

The schematic of the transformer feedback VCO using the asymmetric-width transformer is shown in Fig. 5. Due to the in-phase relationship provided by the drain-to-source feedback, the drain voltage can swing above the supply voltage and below the ground potential, as shown in [7]. Consequently, the close-in phase noise benefits from the enhanced voltage swing at the VCO output.

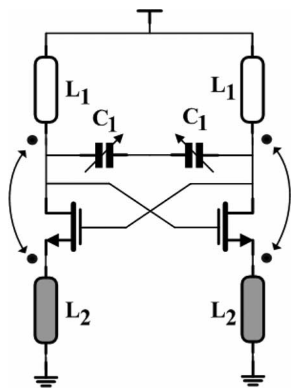


Fig. 5. Drain-to-source feedback VCO using an asymmetric-width transformer.

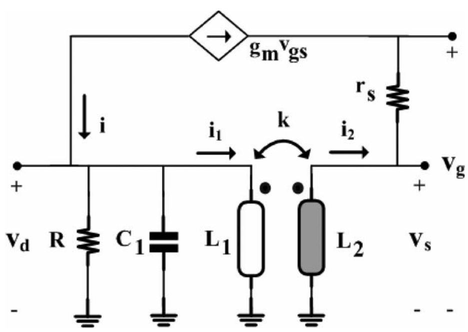


Fig. 6. Equivalent circuit model of a half VCO (gate current $= 0$).

### A. Oscillation Frequency and Startup Conditions

Fig. 6 shows the equivalent circuit of the half VCO using the small signal model [14] and the parallel *LC* tank model [15]. $L_1$, $C_1$, and $R$ comprise the *LC* tank. $C_1$ and $R$ are the tank capacitor and the parallel resistor, respectively, of the primary part of the transformer, which stands for the series loss. $L_1$ and $L_2$ are the primary and secondary parts of the asymmetric-width transformer, and it is assumed that the effect of asymmetric width is reflected. $M$, $k$, and $r_{\mathrm{s}}$ stand for the mutual inductance, the coupling factor, and the source resistance of the metal–oxide–semiconductor field-effect transistor, respectively. The currents through the primary and secondary parts of the transformer are expressed as $i_1$ and $i_2$. An ac current through the transistor is presented as $i$ and the same with the current $i_2$.

Based on the equivalent circuit, the node voltages are given by

$$v_{\mathrm{d}} = \frac{-sR(M+L_1)}{s^2L_1C_1R+sL_1+R} \cdot i \tag{1}$$

$$v_{\mathrm{s}} = \frac{s^3C_1R(M^2-L_1L_2)+s^2(M^2-L_1L_2)-sR(L_2+M)}{s^2L_1C_1R+sL_1+R} \cdot I \tag{2}$$

$$v_{\mathrm{g}} = \frac{s^3C_1R(M^2-L_1L_2)+s^2(M^2-L_1L_2+R_{\mathrm{s}}L_1C_1R)}{s^2L_1C_1R+sL_1+R} \times \frac{s(L_1r_{\mathrm{s}}-RL_2-RM)+r_{\mathrm{s}}R}{s^2L_1C_1R+sL_1+R} \cdot i. \tag{3}$$

The oscillation condition of the oscillator is given by [8]

$$v_{\mathrm{d}}/v_{\mathrm{g}} = -1 \text{ at } s = j\omega_\circ \tag{4}$$

where $\omega_{\mathrm{o}}$ is the oscillation frequency of the VCO. Using (1) and (3), (4) is expressed as follows:

$$\begin{aligned} j\omega_\circ R(L_1+M) = &-j\omega_\circ^3(M^2-L_1L_2)C_1R \\ &-\omega_\circ^2(M^2-L_1L_2+r_sL_1C_1R) \\ &+j\omega_\circ(L_1r_{\mathrm{s}}-RL_2-RM)+r_{\mathrm{s}}R. \end{aligned} \tag{5}$$

The oscillation frequency can be obtained from the condition that makes the real part of (5) to be 0. Applying the basic relation of $M = k\sqrt{L_1L_2}$, the oscillation frequency is given by

$$\omega_\circ = \sqrt{1\Big/L_1 \cdot \left(\frac{L_2(k^2-1)}{r_{\mathrm{s}}R} + C_1\right)}. \tag{6}$$

By applying the imaginary part of (5) to be 0 [8], the startup condition of the half VCO is given as follows:

$$g_{\mathrm{m}} \geq \frac{1}{R} \cdot \frac{L_1}{L_1-L_2}(L_1 > L_2). \tag{7}$$

### B. In-Phase Relationship and Output Voltage Swing

Using $k \approx 1$ and $M = \sqrt{L_1L_2}$, the drain and the source voltage of (1) and (2) are given by

$$v_{\mathrm{d}} = A(s) \cdot (M+L_1) \cdot i \tag{8}$$

$$v_{\mathrm{s}} = A(s) \cdot (L_2+M) \cdot i \tag{9}$$

where

$$A(s=j\omega_0) = \frac{-sR}{s^2L_1C_1R+sL_1+R} = -\frac{R}{L_1}(k \approx 1). \tag{10}$$

Thus, (8) and (9) can be simplified as follows:

$$v_{\mathrm{d}} = -\frac{R}{L_1} \cdot (M+L_1) \cdot i = -R \cdot \left(1+\frac{\sqrt{L_2}}{\sqrt{L_1}}\right) \cdot i \tag{11}$$

$$v_{\mathrm{s}} = -\frac{R}{L_1} \cdot (L_2+M) \cdot i = \frac{\sqrt{L_2}}{\sqrt{L_1}} \cdot v_{\mathrm{d}}. \tag{12}$$

In (11), $R$ is the effective parallel resistance of the resonator at the resonance frequency. Also, the in-phase relationship of the drain and the source voltage is shown in (12). If the oscillator satisfies the startup conditions of (7), then the amplitude of the oscillator will continue to grow until the transistor nonlinearity reduces the gain and enters into steady state with a constant amplitude. In this state, the cross-coupled transistors act as the differential switch driven by the large sinusoidal voltage, which is approximately expressed as a square wave. The differential switch modulates the dc current by the square wave [8], [15]. The current in (11) is approximated by the fundamental current component of the current. From the

Fourier series of the dc current, the fundamental current is given by

$$i = i_{\text{fund}} = i_{\text{dc}} \cdot \frac{2}{\pi}. \tag{13}$$

Thus, the drain voltage of (11) is given by

$$v_{\text{d}} = -R \cdot \left(1 + \frac{\sqrt{L_2}}{\sqrt{L_1}}\right) \cdot \frac{2}{\pi} \cdot i_{\text{dc}}. \tag{14}$$

In conventional *LC*-VCO with effective parallel resistance $R$ at the resonance frequency, the maximum oscillation amplitude of the VCO is given by [7], [8]

$$|v_{\text{conv}}| = R \cdot \frac{2}{\pi} \cdot i_{\text{dc}} \approx v_{\text{DD}}. \tag{15}$$

From (14) and (15), the output voltage swing of the transformer feedback VCO is simply given as follows:

$$v_{\text{d}} \approx \left(1 + \frac{\sqrt{L_2}}{\sqrt{L_1}}\right) \cdot v_{\text{DD}}. \tag{16}$$

As shown in (16), the oscillation amplitude of the transformer feedback VCO is larger than the supply voltage, and the output voltage can swing below the ground potential. Thus, the peak-to-peak voltage can be larger than two times of the supply voltage, which is the maximum limit of the conventional topology. From (16), as the inductance ratio of the transformer becomes nearly 1, the maximum oscillation amplitude of the VCO is obtained, and the phase noise characteristic can be improved [5], [6].

However, the connection of the *LC* tank to the source of the transistor by transformer feedback entails an important design issue. With large signal transconductance of the transistor $G_{\text{m}}$, the resistive loading in parallel to the *LC* tank is equal to $N^2/G_{\text{m}}$ [15]. $N$ is the square root of the inductance ratio of the transformer and is given by [8]

$$N \approx \frac{\sqrt{L_1}}{\sqrt{L_2}}. \tag{17}$$

This parallel resistive loading drastically reduces the Q of the tank, reducing the loop gain and preventing oscillation [15]. Considering the parallel resistive loading by a transformer and $N$ from (17), the effective load impedance of the transformer feedback VCO is different from the parallel resistance $R$ in Fig. 6, and it is given by

$$R_{\text{load\_eff}} = R \cdot \frac{N^2}{R \cdot G_{\text{m}} + N^2}. \tag{18}$$

Also, from (17), the output voltage swing of (16) is given by

$$v_{\text{d}} \approx \left(1 + \frac{1}{N}\right) \cdot v_{\text{DD}}. \tag{19}$$

From (18), the effective load impedance is increased with the increase in the inductance ratio. In contrast, the oscillation amplitude is increased by the decrease in the inductance ratio, as shown in (19). Thus, there is a careful tradeoff between the oscillation amplitude and the effective parallel resistance to determine the inductance ratio $N$. As mentioned in Section II, an asymmetric-width transformer allows the easy optimization of the inductance ratio and the higher quality factor. The high Q characteristic can give a large value of parallel resistance $R$ of (18). Thus, the asymmetric-width transformer can increase the effective load impedance and also prevent the degradation of the quality factor of the *LC* tank and the loop gain [15].

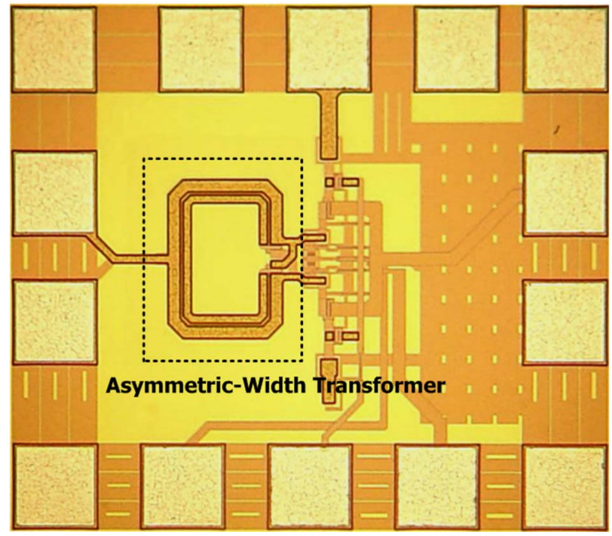


Fig. 7. Microphotograph of the fabricated VCO.

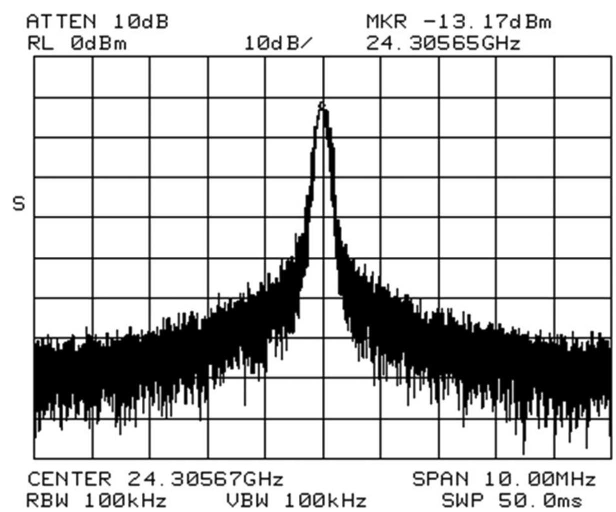


Fig. 8. Output spectrum of the fabricated VCO.

## IV. Measurement of the CMOS 24-GHz VCO Using an Asymmetric-Width Transformer

The transformer feedback VCO using the asymmetric-width transformer is designed and implemented using a one-poly six-metal 0.18-$\mu$m RF CMOS process. The asymmetric-width transformer of the VCO is designed by Agilent ADS and Ansoft Designer from the point of figure of merit. The lengths of the primary and secondary parts of the transformer are 500 and 400 $\mu$m long, respectively. The widths are 15 and 10 $\mu$m wide with 3-$\mu$m spacing. From 2.5D EM simulation, the primary and secondary inductance values are 0.86 and 0.47 nH, and the impedance transform ratio of 1.25 is obtained. In Fig. 7,

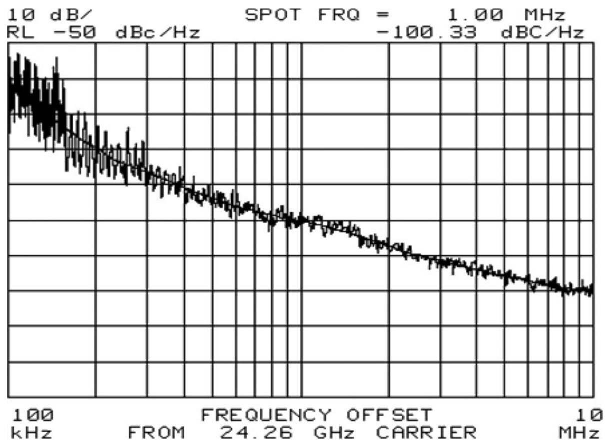


Fig. 9. Measured phase noise of the VCO at 0.65-V supply.

TABLE I
PERFORMANCE SUMMARY OF THE VCO

| | |
|---|---|
| Process | 0.18μm CMOS |
| Frequency (GHz) | 24.27 |
| $V_{DD}/I_{DD}$ (V/mA) | 0.65/12 |
| Power Consumption (mW) | 7.8 |
| Phase Noise (dBc/Hz) @ 1 MHz | -100.33 |
| FOM (dBc/Hz) | -179 |
| Tuning Range | 2.2% |
| Area (Transformer) | 0.7 x 0.6 ($mm^2$) |

the fabricated VCO using the asymmetric-width transformer is represented, which occupies 0.7 $\times$ 0.6 mm, including the pads area.

The output spectrum and the phase noise are obtained using an HP 8564E Spectrum Analyzer and its Phase Noise Measurement Kit. A single-stage buffer is included to reduce the loading effects. The buffer stage consisted of a source follower with a current source load. Also, accumulation-mode devices are used as varactors. The output spectrum and the measured phase noise are given in Figs. 8 and 9. The performance of the VCO is summarized in Table I. The measured phase noise at 1-MHz offset is $-100.33$ dBc/Hz from 0.65-V supply with 7.8 mW of power consumption. The figure of merit of the fabricated VCO is $-179$ dBc/Hz. The figure of merit is defined as

$$FOM = L\{\Delta f\} + 10\log\left[\left(\frac{\Delta f}{f_{\mathrm{osc}}}\right)^2 \cdot P_{\mathrm{dc}}\right] \tag{20}$$

where $L\{\Delta f\}$ is the phase noise measured at $\Delta f$ offset from $f_{\mathrm{osc}}$ carrier frequency, and $P_{\mathrm{dc}}$ is the dc power consumption in milliwatts.

## V. CONCLUSION

A 24-GHz voltage-controlled oscillator has been implemented using a one-poly six-metal 0.18-$\mu$m RF CMOS process. The drain-to-source feedback VCO using an asymmetric-width transformer has been proposed, which allows the easy optimization of the inductance ratio. The fabricated circuit has been characterized with a supply voltage of 0.65 V. It achieves a phase noise of $-100.33$ dBc/Hz at 1-MHz offset, and the figure of merit is 179 dBc/Hz with 7.8-mW power consumption.

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