Efficiency Enhanced and Harmonic Suppressed Differential VCO with Novel Buffer Scheme using Transformers for IEEE 802.11a

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ABSTRACT **— We propose a novel buffer scheme for the cross-coupled differential Voltage-Controlled-Oscillator (VCO) design. Transformers are used for the new buffer configuration. The primary coil of the transformer is the inductor of the LC resonator, and the oscillation signal is extracted through the secondary. We also implement the differential VCO using the conventional buffer, and compare the performance with the VCO using transformer buffer. With transformer buffers, we achieve 5 times efficiency enhancement and 9dBc more harmonic suppression than the conventional structure. The conventional type VCO shows the oscillation frequency of 4.4~5.4 GHz with approximately 0dBm output power using a total current of 15mA. The VCO using transformer buffer shows 4.7~5.1 GHz with 6.5 ±1dBm output power using only 10mA for the cross-coupled core. The 2nd harmonic suppression of each VCO shows -10dBc and -19dBc, respectively. Both show the phase-noise of about -111dBc/Hz at 1MHz offset. To the best of our knowledge, this is the first demonstration of enhancing efficiency and linearity in a VCO using transformer as a buffer stage.**

I. INTRODUCTION

In recent years, the market of IEEE 802.11a applications for high data rate (up to 50Mbps) wireless local area network (LAN) in the 5GHz frequency band with 300MHz bandwidth (5.15~5.35 / 5.725~5.825 GHz), has been rapidly growing for mobile computing, increasing the demand for the high performance RF circuits in the 5GHz band.

One of the critical RF circuit blocks in wireless transceivers is the Voltage-Controlled-Oscillator (VCO). Efficiency, harmonic suppression, tuning range and phase-noise are the important figure-of-merits of the VCO. Because of the limited battery of mobile devices, low power consumption is required. However there is a trade-off between efficiency and phase-noise performance: the more signal power, the better phase-noise performance [1].

A cross-coupled differential topology is commonly used for a VCO. Many papers discussing VCOs designed with a cross-coupled differential topology have been published. In this configuration, two LC resonators are located at each drain side of cross-coupled transistor pair, and the output oscillation signal is extracted through a buffer, which is connected at the resonator node. The role of this buffer stage is the isolation of the resonator node from the next circuit stage to maintain the oscillation condition. A buffer stage is usually designed with a source follower. Sometimes an amplifier stage is placed following the buffer to increase the output power of the oscillation signal.

With the novel buffer scheme proposed in this work, we demonstrate efficiency improvement and harmonic suppression. A transformer buffer makes it possible to remove the source follower and the amplifier stage. In addition, more output power can be obtained. For this reason, a VCO with transformer buffers shows efficiency enhancement compared with conventional cross-coupled VCO design. Furthermore, the notch point in S21 characteristic of transformer can be used to suppress the 2nd harmonic component of the oscillation signal.

A transformer has been used to extract output in a VCO in a previous work [2]. However, this was for the pulling effect, and employed in the amplifier stage. This work, for the first time, uses a transformer directly in the resonator, resulting in significant enhancement in VCO performance.

II. INDUCTOR AND TRANSFORMER DESIGN

We have designed three types of inductor with the different metal thickness, and a vertical type transformer using two inductors designed on different metal layers

A. Inductor for Resonator

Because of a two metal layer process, three types of inductor are available. The first design uses only the first metal layer (Type I), another is designed with only the second metal layer (Type II), and the last one is an inductor stacking two metal layers (Type III). Table I is the summary of inductor performance at 5GHz.

The performance of type II and type III are very similar. And the inductance value of three types is almost identical. Fig. 1 shows the inductor performance of type I and type II.

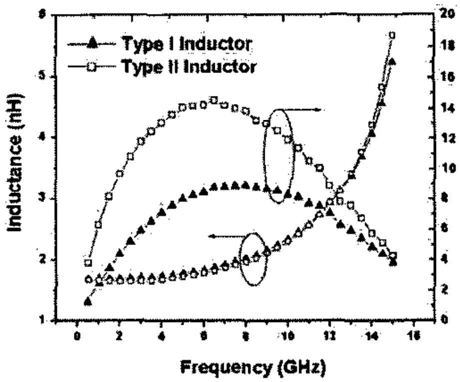


Fig. 1. Measured performance of type I and type II inductor

TABLE I
SUMMARY OF INDUCTOR PERFORMANCE AT 5GHZ

Inductor	Type I	Type II	Type III
Metal Thickness	2μm	4μm	6μm
Inductance	1.7nH		
Quality Factor	8	14	

B. Transformer for Buffer

For the novel buffer configuration in the differential VCO, the vertical coupling type transformers are designed with type I and type II inductors, as shown in Fig. 2. The type II inductor is used for the primary coil, and the type I for the secondary, because the primary takes the role of the resonator, and has higher quality factor than the secondary.

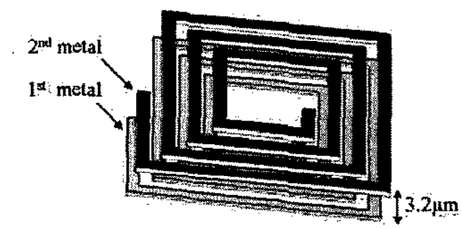


Fig. 2. Structure of vertical type transformer

The transformers are designed to use the magnetic coupling characteristic region [3]. The null point of S21 is designed to be located at the 2^{nd} harmonic oscillation frequency, so that the linearity is increased. The minimum insertion loss is –6dB at 5GHz, and the null point is –18dB at 10GHz, as shown in Fig. 3.

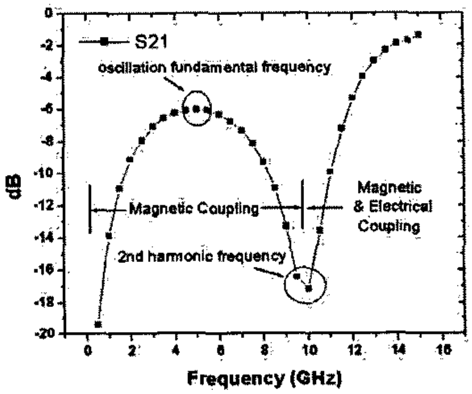


Fig. 3. Measured S21 characteristic of transformer

III. DIFFERENTIAL VCO CIRCUIT DESIGN

We designed two differential VCOs for IEEE 802.11a WLAN application. One is the VCO with the conventional buffer stage using the source follower (Type A), and the other with the transformer buffers (Type B). Table II shows the performance comparison of these two VCOs and the VCO published in [2].

TABLE II
COMPARISON OF VCOS PERFORMANCE

VCO	Type A	Type B	[2]
Center Frequency	4.9GHz		4.4GHz
Tuning Range	1GHz	400MHz	1GHz
Output Power	0dBm	7dBm	-6.5dBm
Current for core	10mA		4mA
Current for buffer	5mA	none	14mA
Phase-Noise(@1MHz)	-111dBc/Hz		-110dBc/Hz

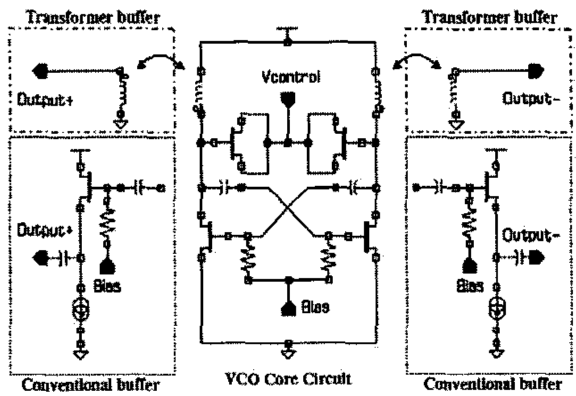
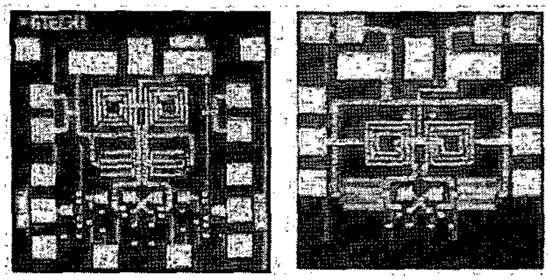


Fig. 4. Schematic of VCO circuit with source follower buffer and transformer buffer

A commercial 0.6 μm TQTRx two metal layer process was used to design the VCO. Fig. 4 is the schematic of VCO circuit showing core circuit and two types of buffer. In order to reduce the up-conversion of 1/f noise, the cross-coupled differential topology with the capacitive coupling feedback was applied [4]. Fig. 5 shows the chip photographs of VCOs with source followers and transformers as buffers.



(a) (b)

Fig. 5. Chip photographs of VCOs with (a) source follower and (b) transformer

A. Conventional Differential VCO

For the conventional design, source followers are directly connected to the resonator nodes (the drain side of cross-coupled pair), as shown in Fig. 4.

Type III inductors, with the inductance of 1.7nH and the quality factor of 14 at 5 GHz, are used for the resonator. Varactors are implemented using 480 μm FETs with the drain and the source connected together. The quality factor of varactors is 27 and 60 at an applied control voltage ($V_{control}$) of 0 and 3V, respectively, at 5 GHz.

Source follower buffers make it possible to probe with 50Ω. Almost all differential VCOs, published previously, have been designed with the source follow buffer stages so as not to disturb the oscillation condition.

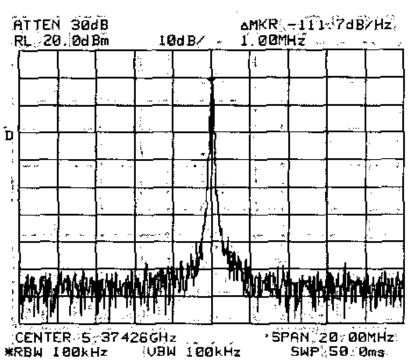


Fig. 6. Oscillation frequency and phase-noise performance of VCO with conventional source follower buffer

The oscillation frequency varies between 4.4GHz and 5.4GHz with the applied control voltage from 2.5V to 0V. The tuning range is about 1GHz (20%) and the output power is approximately 0dBm. The performance is shown and compared with the VCO using transformer in Fig. 7. The VCO is designed to meet the entire frequency range of IEEE 802.11a WLAN using an IF band with a center frequency of 650MHz. The phase-noise performance shows −111.7dBc/Hz at an offset frequency of 1MHz with 5.37GHz carrier frequency, as shown in Fig. 6.

B. Differential VCO with Transformer Buffers

a. Efficiency Enhancement

Transformers can be used as buffer stages instead of the conventional source followers. The resonator part of cross-coupled differential VCO is located at the drain side of cross-coupled active devices. For this reason, the peak-to-peak voltage swing ($V_{P\text{-}P}$) at the resonator nodes can be ideally twice of the supply voltage. Even if the $V_{P\text{-}P}$ is very high, the output swing of the VCO is much smaller than the voltage swing at the resonator node because of the source follower. When the outputs of LO go into the inputs of a passive mixer, the amplifier stage is necessary to increase LO power.

Using the transformer as a buffer, the buffer stage and the amplifier stage can be removed, which means the reduction in power consumption. In addition, more output power is achievable simultaneously. In this work, the VCO with transformer buffers shows at least 5 times efficiency enhancement over a conventional differential VCO.

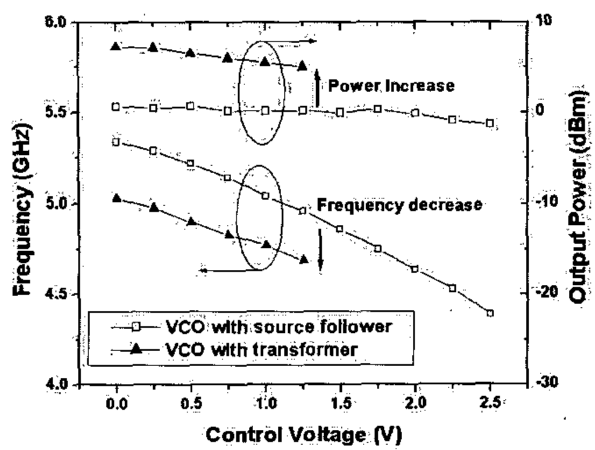


Fig. 7. Measured performance of VCOs with source follower buffer and the transformer buffer

The oscillation frequency and the output power are shown in Fig. 7, as a function of the applied control voltage. The oscillation frequency of the VCO with the transformers is 300MHz lower than that of the VCO with the source followers because the capacitance between the primary and the secondary coil is higher than the gate-source capacitance (Cgs) of the source follower. An improvement of 6~7dB in output power is obtained, as shown in Fig. 7.

b. Harmonic Suppression

When designing transformers, the null point of S21 is designed to be at the frequency of the 2^{nd} harmonic of VCO in order to suppress the 2^{nd} harmonic component. 9dBc more 2^{nd} harmonic suppression is obtained, as shown in Fig 8.

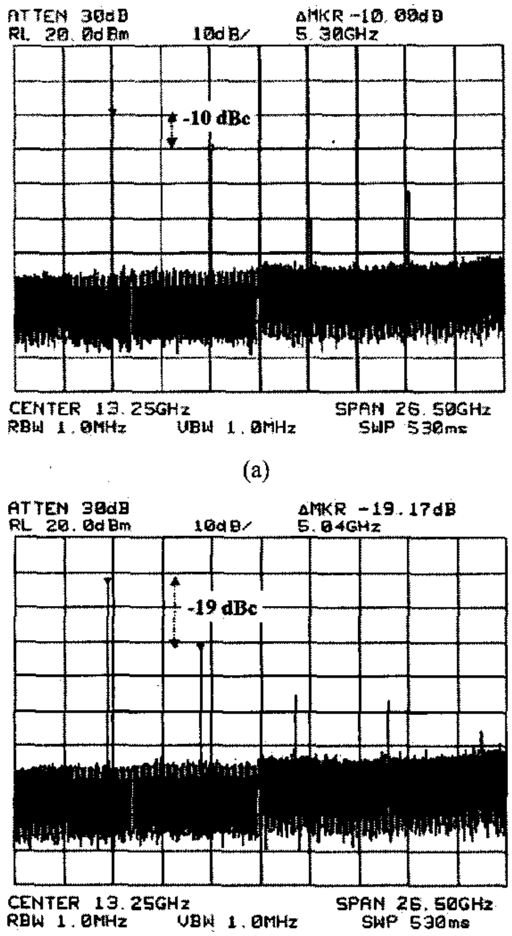


Fig 8. Output spectrum of (a) VCO with source follower buffer, and (b) VCO with transformer buffer

IV. Conclusion

We propose a novel buffer configuration using a vertical type transformer for a VCO with cross-coupled differential topology. Applying the transformer buffer to the VCO design, efficiency enhancement and harmonic suppression are demonstrated in this work compared with the conventional type differential VCO.

The differential VCO using the conventional source follower buffer shows the performance covering the entire frequency range of IEEE 802.11a WLAN, and the VCO using the transformer buffer scheme can be used for the two lower bands.

Acknowledgement

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