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A Capacitively Coupled Multi-Stage LC Oscillator

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* *Short Paper*

Abstract: Coupling with a ring of capacitors introduces in-phase coupling current in multi-stage LC oscillators, increasing coupling strength and phase spacing accuracy. Capacitive coupling is effective at high-frequency applications because it increases coupling strength with the operating frequency. However, capacitive loading from the ring lowers operating frequency and reduces the tuning range. Mathematical expressions of phase noise and phase spacing accuracy with capacitive coupling are examined here, and transistor-level simulations confirm the effectiveness of the capacitive coupling.

Keywords: **LC oscillator, Multi-stage, Phase noise, Capacitive coupling**

1. Introduction

A single-stage LC oscillator operates at a frequency that satisfies its oscillation conditions. Under these conditions, both the current and the voltage of the LC tank are in phase. However, for a multi-stage coupled LC oscillator, out-of-phase coupling current is introduced in each stage from the adjacent stage, which changes the operating frequency and degrades the quality factor of an LC tank [1]. While phase noise in a multi-stage oscillator typically depends on the quality factor of the LC tank, phase spacing accuracy is related to the strength of the coupling signal [2]. Unlike conventional coupling with coupling transistors, capacitive coupling introduces a large in-phase coupling current from the adjacent stages without degrading the quality factor of an LC tank. Therefore, capacitive coupling can achieve both low-phase noise and accurate phase spacing.

2. Capacitive Coupling

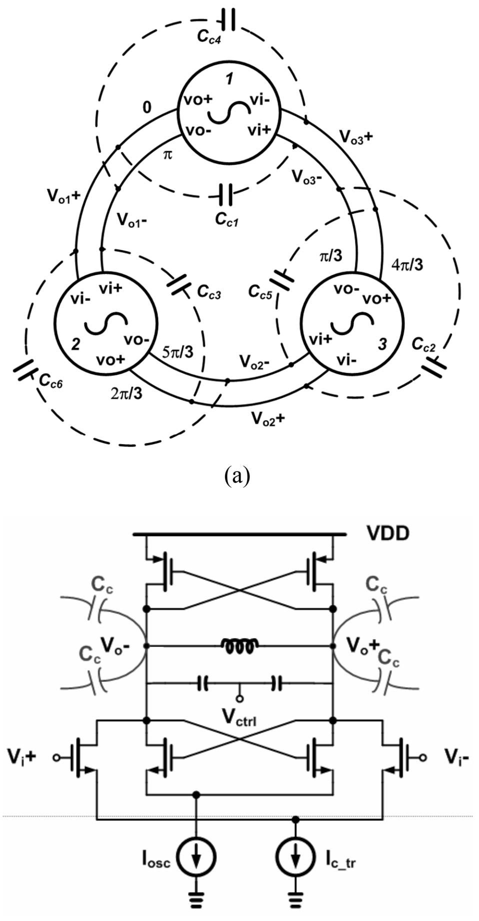
Capacitive coupling can be accomplished using a ring of capacitors, as seen in Fig. 1(a) [3-5]. The three-stage coupled oscillator with the basic oscillator stage seen in Fig. 1(b) accompanies both conventional coupling with transistors (solid lines) and capacitive coupling (dashed lines). Even though capacitive coupling alone can provide multi-phases, coupling with coupling transistors is also used to accurately define oscillation direction and phase sequences. Based on the fact that V_i+ in the basic cell ideally leads $\pi/3$ degrees to V_o+, Fig. 1(a) shows the phases on output, and the capacitors connect the oscillator output nodes in the order of the phases, forming a ring.

A phasor diagram of a three-stage coupled LC oscillator with capacitive coupling is shown in Fig. 2. Each oscillator output node contains three current components. For example, node V_{o1}+ contains a regeneration current, I_{osc1}, with two coupling currents: one is a coupling current produced by coupling transistors, I_{c_tr3}-, and the other is a coupling current introduced by the coupling capacitors, I_{c_cap1}.

With the assumption that the voltage at V_{o1}+, V_{o2}-, and V_{o3}- are $V_o\cdot\cos(\omega_{res}t)$, $V_o\cdot\cos(\omega_{res}t-\phi)$, and $V_o\cdot\cos(\omega_{res}t+\phi)$, respectively, the current contributed to the V_{o1}+ node through the coupling capacitors, I_{c_cap1}, is the sum of the two current components, I_{c_cap13b} and I_{c_cap2b1}, in Eq. (1), and the phase of I_{c_cap1} is the same as the phase of V_{o1}+.

$$i_{c\_cap1} = 2C_c V_o \omega_{res} \sin\phi \cos(\omega_{res} t) \tag{1}$$

With this large in-phase coupling current at gigahertz operations, the total coupling current in Eq. (2), becomes a vector sum with the coupling current through coupling transistors, I_{c_tr3}-, resulting in much greater coupling current magnitude in Fig. 2.



(a)

(b)

Fig. 1. Three-stage LC oscillator with a ring of capacitors (Fig. 1(a)), and a basic oscillator stage (Fig. 1(b)).

$$i_{c1} = \left(i_{c\_tr3-}{}^2 + i_{c\_cap1}{}^2 + 2\left|i_{c\_tr3-}\right|\left|i_{c\_cap1}\right|\cos\phi\right)^{1/2} \qquad (2)$$

An additional benefit with the large in-phase coupling current is that the phase difference between the total coupling current and the regeneration current becomes smaller in Fig. 2 from the phase difference without capacitive coupling, ϕ_{con}, in Eq. (3) [2, 6] compared to that with capacitive coupling, ϕ_{cap}, in Eq. (4), because the denominator in the parentheses grows faster with the capacitive coupling current.

$$\phi_{con} = \cos^{-1}\left(\frac{\left|i_{osc1}\right| + \left|i_{c\_tr3-}\right|\cos\phi}{\left(i_{osc1}{}^2 + i_{c\_tr3-}{}^2 + 2\left|i_{osc1}\right|\left|i_{c\_tr3-}\right|\cos\phi\right)^{1/2}}\right) \qquad (3)$$

$$\phi_{cap} = \cos^{-1}\left(\frac{\left|i_{osc1} + i_{c\_cap1}\right| + \left|i_{c\_tr3-}\right|\cos\phi}{\left(\left(i_{osc1} + i_{c\_cap1}\right)^2 + i_{c\_tr3-}{}^2 + 2\left|i_{osc1} + i_{c\_cap1}\right|\left|i_{c\_tr3-}\right|\cos\phi\right)^{1/2}}\right) \qquad (4)$$

The smaller phase difference with capacitive coupling in Eq. (4) increases the effective quality factor of the LC tank, resulting in lower phase noise [6].

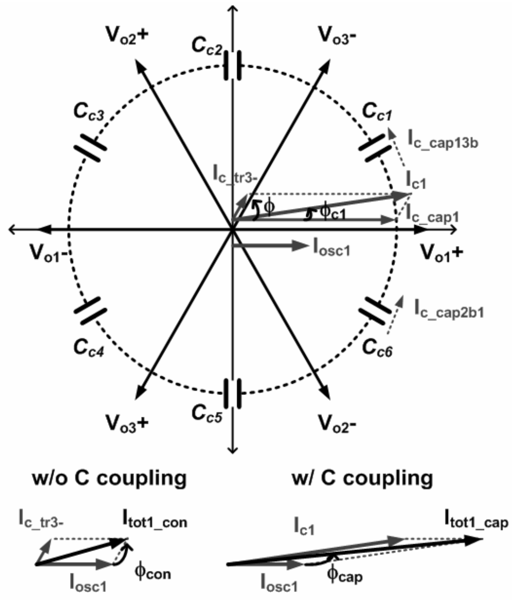


Fig. 2. Phasor diagram of a three-stage LC oscillator ring with capacitive coupling, and comparison of the coupling current magnitude and phase differences between one without capacitive coupling and one with capacitive coupling.

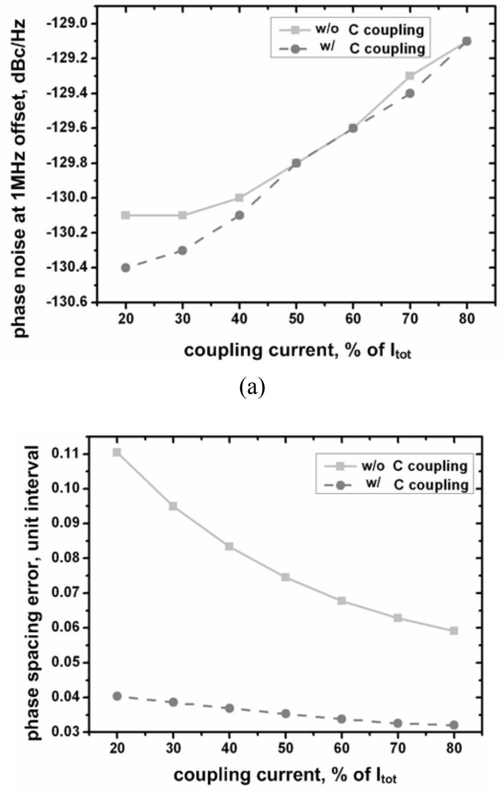
Phase spacing error in multi-stage coupled LC oscillators can be expressed as standard deviation, σ_ϕ, of the phase spaces in Eq. (5), where m is the ratio of the coupling current to the regeneration current (I_c/I_{osc}), and ϕ is the phase difference introduced to an LC tank [2].

$$\sigma_\phi = \frac{\sigma_\omega}{\omega_{res}} \cdot 2Q \cdot \sqrt{\frac{N-1}{N}} \cdot \frac{\left(1 + m\cos\phi\right)^2}{m\left(m + \cos\phi\right)} \qquad (5)$$

As m increases with capacitive coupling in Eq. (2), phase spacing error in terms of σ_ϕ becomes smaller because the denominator in the last term in Eq. (5) grows faster than the numerator, resulting in accurate phase spacing. However, the phase difference in the voltages across the coupling capacitors causes capacitive loading, lowering the operating frequency and reducing the tuning range [4].

3. Simulation

Two three-stage coupled oscillators are designed to operate at 4.5GHz with Taiwan Semiconductor Manufacturing Corporation (TSMC) 0.18μm technology, but only one oscillator has a ring of 1pF metal-insulator-metal (MIM) capacitors taking advantage of in-phase capacitive coupling current, and the other one has equivalent capacitive loading. The LC tank is comprised of an 858pH spiral inductor with a quality factor of approximately 8 at 4.5GHz and a series of varactors. With the basic oscillator stage in Fig. 1(b), the amount of



(a)

(b)

Fig. 3. Comparison of phase noise with/without capacitive coupling (Fig. 3(a)) and phase spacing error (Fig. 3(b)).

coupling current through coupling transistors can be controlled. With a deliberate mismatch (i.e., *50 fF* extra capacitance in one of the six output nodes), the phase noise and the phase spacing error for different transistor coupling current settings (expressed as a percentage of I_{tot} (6mA)) are plotted in Figs. 3(a) and (b), respectively. Even though the two oscillators operate at the same frequency, in the presence of the same mismatch, the oscillator with capacitive coupling performs at 0.3dB less phase noise with 20% of the total current for the coupling transistors and substantially less phase spacing error: a 0.07 unit interval phase spacing error improvement at the same operating point.

4. Conclusion

Capacitive coupling in multi-stage coupled LC oscillators introduces in-phase coupling current, improving phase noise performance and phase spacing accuracy. Mathematical derivation and simulation shows the effectiveness of capacitive coupling. Capacitive coupling can be easily extended to any number of stages and provides an accurate and finely spaced clock system for clock-and-data recovery and other applications.

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