Low-Power LC-Tank-Reused Injection-Locked Frequency Multiplier

Invited Paper

Chirn Chye Boon, Kiat Seng Yeo, Manh Anh Do and Yannan Miao
Virtus, 50 Nanyang Avenue, Block S3.2, Level B2,
School of Electrical and Electronic Engineering, Nanyang Technological University
Singapore 639798
eccboon@ntu.edu.sg; eksyeo@ntu.edu.sg; emado@ntu.edu.sg; miao0012@e.ntu.edu.sg.

***Abstract*— In this paper a new topology of injection-locked frequency multiplier (ILFM) with high conversion gain and low power consumption is proposed. This new topology is employed to design a multiply-by-2 (×2) ILFM with differential input. The ILFM consists of a double-balanced Gilbert-cell mixer and an injection-locked oscillator (ILO) with only one LC tank. Equations of the ILFM's operation range and conversion gain will be derived mathematically. The circuit was fabricated in 0.18 µm CMOS technology. At a supply voltage of 1.8 V, the measured total power consumption is 6.66 mW. With an input power of 0 dBm, the ILFM has a conversion gain from -0.4 dB to 4.5 dB and its output-frequency range is from 12 GHz to 16.4 GHz.**

I. Introduction

A major obstacle to the implementation of a transceiver operating at high-frequency is the degradation of passive and active components with increasing frequency. This problem is particularly severe in a frequency synthesizer due to its high operating frequency. Generally, it is necessary to increase power consumption to achieve higher operating frequency.

A frequency multiplier is an attractive approach to generate high-frequency signal with low power consumption. It is driven by a phase-locked loop (PLL), which operates at low frequency and consumes low power [1]. However, generally, it is more difficult to design such a frequency multiplier compared to a frequency divider [2,3,11]. In [4,5], the designs exploited the nonlinearity of active devices to generate the harmonics of the input signal, however, these circuits require many inductors. In [6,7], an up-conversion mixer was used in the frequency multiplier but these circuits had low conversion gain and high power consumption.

In this paper, a novel topology will be proposed and a ×2 injection-locked frequency multiplier (ILFM) employing this novel topology will be shown. In Section II, this novel topology will be compared with the conventional topology. The schematic of the proposed ILFM will be discussed and the magnitude of the injection current will be expressed mathematically. The equations for the operation range and conversion gain of the proposed ILFM will be derived and analyzed. In Section III, the experimental results will be shown and summarized to verify the derived equations. In Section IV, conclusions will be drawn after comparing with other frequency multipliers.

II. Injection-Locked Frequency Multiplier

A. *Proposed topology of frequency multiplier*

A conventional frequency multiplier in Figure 1(a) consists of a frequency pre-generator and an amplifier. The frequency pre-generator is designed based on an up-conversion mixer with both inputs connected to the differential signal v_{in+} and v_{in-} at a frequency f_{in}. The mixer's output v_{m+} and v_{m-} are at $2f_{in}$, connected to an LC tank H_1 and to a pair of transconductance *Gm*. With another LC tank H_2 as a bandpass filter, the frequency multiplier's output v_{out+} and v_{out-} are at a frequency f_{out}, which is also equal to $2f_{in}$. Note that v_m is amplified to v_{out} based on a voltage gain characteristic of the amplifier, which is also shown in Figure 1(a). With increasing v_m, the gain is generally reduced due to the saturation of the amplifying transistor.

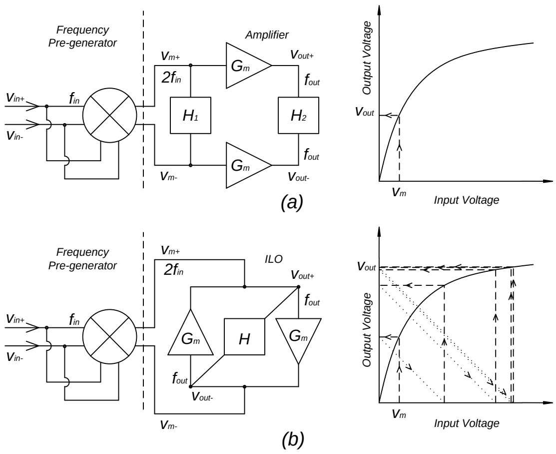

Figure 1. (a) The conventional topology and the amplifier's voltage gain (b) the proposed topology and the ILO's voltage gain.

The proposed topology of the frequency multiplier is shown in Figure 1(b), which has the same frequency pre-generator as in Figure 1(a). An injection-locked oscillator (ILO) is in the following stage instead of the amplifier as in Figure 1(a). In the ILO, a pair of *Gm* forms a positive loop with an LC tank *H*, which serves as a load. When the ILO is injection-locked, f_{out} is equal to $2f_{in}$. In Figure 1(b), it is also shown that v_m is amplified multiple times in the positive feedback loop until the gain reduces to one due to gain compression as input increases. Thus, with the same v_m and characteristic of the voltage gain, v_{out} is larger in Figure 1(b) than in Figure 1(a), especially with small v_m. Note that the input to ILO is in current rather than voltage, v_m is used here for simple illustration. The overall conversion gain of the frequency multiplier is higher in the proposed topology than in the conventional topology with the same power consumption.

B. Analysis of the proposed ILFM

Based on the proposed topology, the schematic of the proposed ×2 ILFM is designed and shown in Figure 2. In the circuit, the mixer is designed based on a double-balanced Gilbert cell, which consists of six NMOS transistors. M_{n1} and M_{n2} form a transconductance stage and are biased by a dc voltage V_{B1} (not shown). M_{n3}, M_{n4}, M_{n5} and M_{n6} form a switching stage and are biased by another dc voltage V_{B2} (not shown). The inputs v_{in+} and v_{in-} of the proposed circuit are a pair of differential signal from signal generator or low-frequency PLL. M_{n1}, M_{n3}, and M_{n6} are connected to v_{in+} while M_{n2}, M_{n4}, and M_{n5} are connected to v_{in-}. The differential injection currents i_{inj+} and i_{inj-} are generated from the mixer and connected to the following ILO.

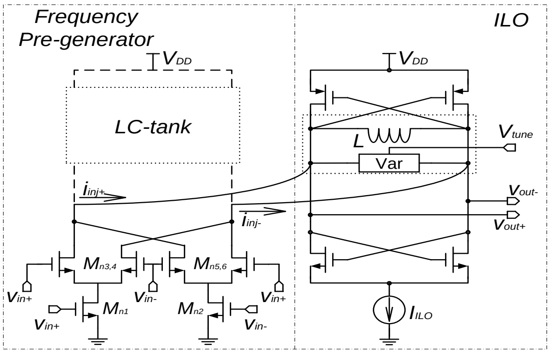

Figure 2. Schematic of the proposed ×2 ILFM.

Based on a complementary structure with an LC tank, the ILO consumed a dc current I_{ILO} to keep its self-oscillation at a resonant frequency f_0. The LC tank is also used as the load of the mixer, which serves as a bandpass filter. Only the frequency close to f_0 is selected at the output of the mixer. If $2f_{in}$ is close to f_0, the ILO is injection-locked to the injection current's frequency f_{inj}, which is equal to $2f_{in}$. Thus, f_{out} is exactly equal to $2f_{in}$. The outputs v_{out+} and v_{out-} are connected to a buffer for measurement. An additional dc voltage V_{tune} is connected to a varactor in the ILO, which is used to tune f_0 by changing the capacitance of the ILO's LC tank and to further extend the operation range of the ILFM.

In Figure 3, the simulated output amplitude versus input amplitude has been shown for both the proposed ILFM and the conventional frequency multiplier. Both these two frequency multipliers consume the same power. As expected, the ILFM has higher conversion gain than the conventional frequency multiplier. With a small input, the conventional frequency multiplier's output is also small. However, the proposed ILFM with the same input signal consistently has large output signal. This enables us to reduce the input signal from its previous stage.

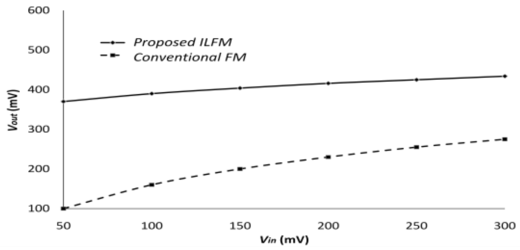

Figure 3. The simulated output amplitude versus input amplitude for both the proposed ILFM and the conventional frequency multiplier.

In the frequency pre-generator, the double-balanced Gilbert-cell mixer has wide dynamic range, which is much wider than the ILO's locking range. With proper design of f_0, the ILFM's operation range Δf is only limited by the later. Similar analysis as [8], the ILFM's operation range can be expressed as

$$\Delta f = \frac{f_0}{Q} \cdot \frac{I_{INJ}}{\sqrt{I_{ILO}^2 - I_{INJ}^2}} \quad (1)$$

where I_{INJ} is the magnitude of the injection current and Q is a quality factor of the LC tank.

The open-loop characteristic of the LC tank in the ILO is shown in Figure 4(a).

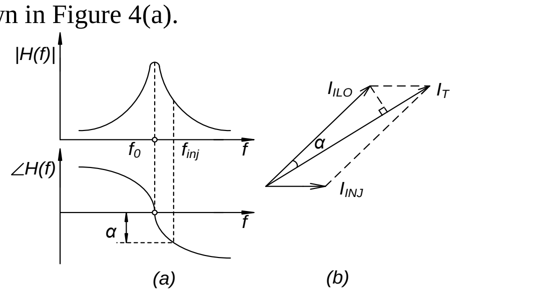

Figure 4. (a) Open-loop characteristic and (b) phasor diagram of the LC tank in the ILO.

In the vicinity of resonance, a phase shift α is caused by I_{INJ}.

$$tan\, \alpha \approx \frac{2Q}{f_0} \cdot \left| f_0 - f_{inj} \right| \quad (2)$$

Thus, sine and cosine of α can be expressed as

$$\cos \alpha = \frac{f_0}{\sqrt{f_0^2 + 4Q^2 \left(f_0 - f_{inj}\right)^2}} \quad (3)$$

$$\sin \alpha = \frac{2Q \left| f_0 - f_{inj} \right|}{\sqrt{f_0^2 + 4Q^2 \left(f_0 - f_{inj}\right)^2}} \quad (4)$$

When the ILO is injection-locked, the phase difference of I_{ILO} and I_{INJ} is smaller than (π/2). Through the phasor diagram in Figure 4(b), their sum I_T is shown and derived geometrically.

$$I_T = I_{ILO} \cdot \cos \alpha + \sqrt{I_{INJ}^2 - (I_{ILO} \cdot \sin \alpha)^2} \quad (5)$$

By substituting (3) and (4) into (5)

$$I_T = \frac{I_{ILO} \cdot f_0 + \sqrt{I_{INJ}^2 \cdot \left(f_0^2 + 4Q^2 \left(f_0 - f_{inj}\right)^2\right) - I_{ILO}^2 \cdot 4Q^2 \left(f_0 - f_{inj}\right)^2}}{\sqrt{f_0^2 + 4Q^2 \left(f_0 - f_{inj}\right)^2}} \quad (6)$$

In [9] , the output swing V_{OUT} can be expressed as

$$V_{OUT} = I_T \cdot |H(f)| \quad (7)$$

where the effective impedance *H(f)* of the LC tank can be expressed as

$$H(f) = \frac{R_p}{1 + j2Q\left|\frac{f_0 - f_{inj}}{f_0}\right|} \quad (8)$$

where R_p is the effective resistance of the LC tank. By substituting (6) and (8) into (7)

$$V_{OUT} = \frac{I_{ILO} \cdot f_0^2 R_P + f_0 R_P \sqrt{I_{INJ}^2 \cdot \left(f_0^2 + 4Q^2 (f_0 - f_{inj})^2\right) - I_{ILO}^2 \cdot 4Q^2 (f_0 - f_{inj})^2}}{f_0^2 + 4Q^2 (f_0 - f_{inj})^2} \quad (9)$$

Consequently, the proposed ILFM's conversion gain can be expressed as

$$\frac{V_{OUT}}{V_{IN}} = \frac{I_{ILO} \cdot f_0^2 R_P + f_0 R_P \sqrt{I_{INJ}^2 \cdot \left(f_0^2 + 4Q^2 (f_0 - f_{inj})^2\right) - I_{ILO}^2 \cdot 4Q^2 (f_0 - f_{inj})^2}}{V_{IN} \cdot \left[f_0^2 + 4Q^2 (f_0 - f_{inj})^2\right]} \quad (10)$$

III. EXPERIMENTAL RESULTS

The proposed ILFM has been designed and fabricated in the 0.18 μm CMOS technology. The die microphotograph is shown in Figure 5. The die area is 0.55 mm × 0.38 mm. With the supply voltage of 1.8 V, the current and power consumption for the core circuit are 3.7 mA and 6.66 mW, respectively.

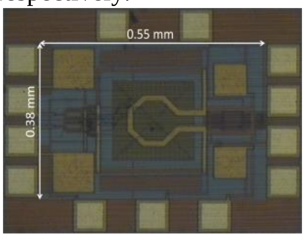

Figure 5. Die micrograph of the proposed ×2 ILFM.

In Figure 6, the measured input sensitivity of the ILFM is shown. With V_{tune} of 0 V and the 0 dBm input, the input-frequency range of the ILFM is 7 GHz to 8.2 GHz. By varying V_{tune} from 0 V to 1.8 V, the input-frequency range is shifted to the left because of f_0 changed from 15 GHz to 13.2 GHz. Thus, with the 0 dBm input and varying V_{tune}, the overall input-frequency range is 6 GHz to 8.2 GHz. As shown in Figure 6, even with the -10 dBm input, the overall input-frequency range is still 6.6 GHz to 7.5 GHz. In Figure 7, the measured output power versus the output frequency is shown. With the 0 dBm input, the ILFM's output-frequency range is 12 GHz to 16.4 GHz. The output power is reduced when the output frequency is deviated from f_0. Through varying V_{tune}, f_0 can be shifted. Hence, higher output power can be obtained, which can be kept higher than 0 dBm in the output-frequency range from 12.4 GHz to 16.4 GHz.

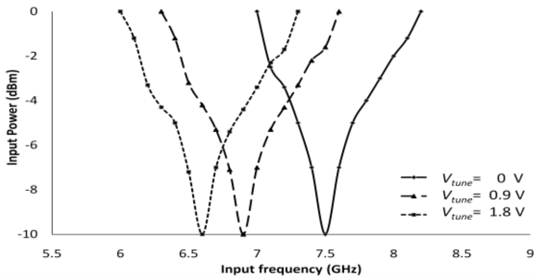

Figure 6. The measured input sensitivity with various V_{tune}.

In Figure 8, the fundamental rejection (FR) in the measured output spectrum is shown. In the proposed ILFM with the 0 dBm input and the 3.7 mA consumed current, the FR is better than 38 dB with reference to the desired frequency at the output. It can be seen that this proposed ILFM is suitable for even-order frequency multiplier as only even-order harmonics of the input frequency can be generated by the doubled-balanced mixer.

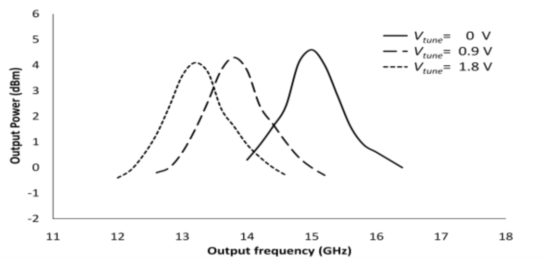

Figure 7. The measured output power versus its output frequency with various V_{tune}.

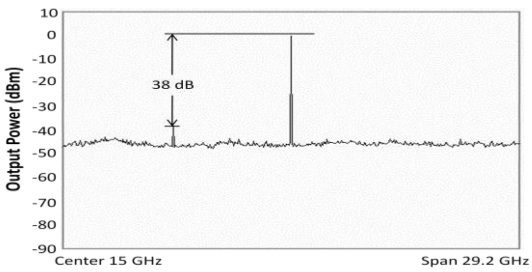

Figure 8. The measured output power spectrum of the input and desired frequencies.

In Figure 9, the operation range and conversion gain versus the input power of the ILFM is shown, where the consumed current is 3.7 mA and the output frequency is selected to be 0.3 GHz from f_0. Note that if the output frequency is selected to be at f_0 the conversion gain obtained will be higher as shown in Figure 7 due to the higher output power. When the input power is changed from -5 dBm to 2 dBm, both the calculated and measured operation ranges are increased. Conversely, both the calculated and measured conversion gains are reduced with the input power due to gain compression.

In Figure 10, the operation range and conversion gain versus I_{ILO} is shown. Similarly, the input power is 0 dBm and the output frequency is selected to be 0.3 GHz from

f_0. It can be observed that both the calculated and measured operation ranges are reduced with increasing I_{ILO} and the measured results match well with the calculated results. It can also be seen that both the calculated and measured conversion gain are increased with increasing I_{ILO}. However, the increment in the measured result is smaller than that in the calculated result after I_{ILO} is larger than 4 mA. This is because that the ILO will go into voltage limited region [9] when I_{ILO} is very large, as its output voltage is clipped by the supply voltage.

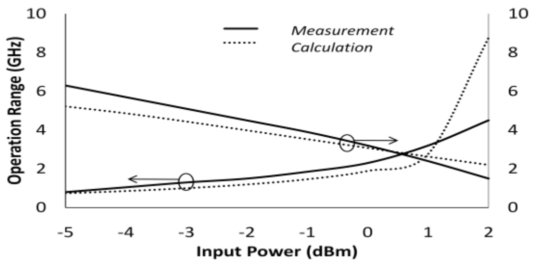

Figure 9. The operation range and conversion gain versus its input power.

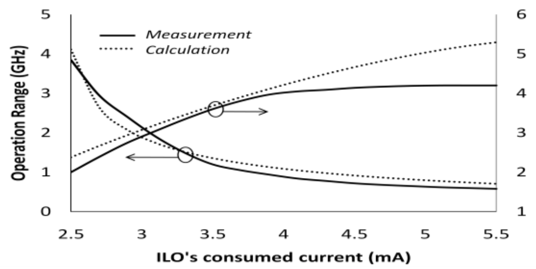

Figure 10. The operation range and conversion gain versus the ILO's consumed current.

IV. CONCLUSION

The proposed ILFM has been designed and fabricated in the 0.18 μm CMOS technology. Based on the analysis, the performance of the proposed circuit is optimized in the design. From the well-matched calculated and measured results, the equations of the operation range and conversion gain have been verified. In Table I, comparisons are made against other frequency multipliers. To compare the performance between different types of frequency multipliers, a figure of merit (*FoM*) is defined as

$$FoM = 10\log\left(\frac{P_{out}}{P_{in}+P_{DC}}\right) + FR + 20\log\left(\frac{\Delta f}{f_{out}}\right) + 30$$

where P_{out} is the output power, P_{in} is the input power, P_{DC} is the dc power consumption, *FR* is the fundamental rejection and ($\Delta f/f_{out}$) is the ratio between operation range and output frequency. An arbitrary number of 30 is added to keep *FoM* of all works positive for easy comparison.

In most of the integrated circuit transceiver, the frequency multiplier's output is connected to mixer and prescaler which can be considered as high impedance outputs. Hence, the voltage gain is more important than the power gain. Nevertheless, for comparison with other works which mostly published the conversion gain in power gain, results for this novel work have been presented in power gain with 50 Ω as the input/output reference impedance.

From Table 1, it can be seen that this work achieves the lowest power consumption and the best *FoM*. The proposed ILFM can be used to generate high frequency output using just one LC tank with low ac and dc power requirements.

TABLE I. COMPARISON WITH PUBLISHED FREQUENCY MULTIPLIERS

	[4]	[5]	[6]	[10]	This work
Technology (CMOS)	0.18 μm	0.18 μm	0.18 μm	0.18 μm	0.18 μm
Multiplier	2	2	3	2	2
Supply Voltage (V)	2.6	1.8	1.5	1.3	1.8
DC Power (mW)	20.8	12.6	7.5	10.5	6.66
Input Power (dBm)	0	-7	10	2	0
f_{out} (GHz)	20~24	5.2~5.8	18~24	18~26	12~16.4
Conversion Gain (dB)	>-4.5	>0	>-17	>-12	>-0.4
FR (dBc)	30~50	20	10~23	30~40	38~45
FoM	26.93	12.7	9.7	30.39	48.59

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