A 440-µW 60-GHz Injection-Locked Frequency Divider in 65nm CMOS

Yue Chao, and Howard C. Luong

Hong Kong University of Science and Technology, Hong Kong, China

***Abstract* — An ultra-low-power millimeter-wave injection-locked frequency divider (ILFD) based on transformer-feedback and transformer-distribution technique is proposed to operate with a very small injection signal. The proposed ILFD measures a locking range from 60.9GHz to 64.7GHz with -7dBm input power while consuming 440uW, which features the minimum power consumption among all the reported V-band frequency dividers. An interesting injection-saturation phenomenon is also identified and verified by measurement results.**

***Index Terms* — ILFD, millimeter-wave, mmW, ultra-low power, transformer feedback, transformer distribution**

I. INTRODUCTION

Existing millimeter-wave (MMW) injection-locked frequency dividers (ILFD) and injection-locked frequency multipliers (ILFM) consume large power (>1.5mW). Moreover, their locking range (LR) is dramatically reduced as the input power drops below 0dBm. On the other hand, more interestingly, when the input power is above certain value, LR of ILFD would also drop, which is contradictory to common sense. This injection-saturation phenomenon, which has never been reported before, will be identified, analyzed and verified by measurement results in this work. Furthermore, transformer-feedback (TF) technique [1] is utilized to lower supply voltage and power consumption. The transformer is further utilized to distribute the parasitic capacitance of tank and thus enhance LR with small injection. Based on TF and transformer-distribution (TD) technique, an ultra-low-power ILFD (ULP-ILFD) is proposed, which measures a LR from 60.9GHz to 64.7GHz with -7dBm input power while consuming 440uW from a 0.85V supply voltage.

This paper is organized as follows. Section II discusses the injection-saturation phenomenon. The proposed ULP-ILFD based on TF and TD technique is discussed in Section III. Measurement result is presented in Section IV and conclusion is drawn in Section V.

II. INJECTION-SATURATION PHENOMENON

Conventionally, LR of ILFD can be enhanced by increasing input power. However, an interesting injection-saturation phenomenon is that there exists a maximum input power beyond which the ILFD fails to lock. According to [2], the injection device M_{inj} of conventional direct-injection ILFDs can be modeled more accurately as an ideal mixer in parallel with a resistor R as shown in Fig. 1(a). From Fig. 1(b), when the injection power is large enough, M_{inj} operates in a class-AB mode and is "on" for more than half of the input period with a large V_{gs} and V_{gd}. Consequently, more current flows through $M_{inj,}$ and the equivalent R decreases. The average resistance of R in a period can be estimated based on large-signal analysis:

$$\overline{R} \approx \frac{\pi}{K_n{}' \dfrac{W}{L} A_{inj}} \tag{1}$$

Here K_n' is the conduction parameter of M_{inj} while W and L represent the size of M_{inj}. Obviously, when amplitude of input signal A_{inj} increases, the average resistance R and tank Q decreases, which would degrade the gain condition and cause the ILFD to fail to lock. Fig. 1(c) shows the simulated input sensitivity curve of conventional ILFD. Consistent with the observation and analysis above, when the input power is larger than -1dBm, the ILFD starts to suffer from injection-saturation problem. LR decreases as the input power increases and eventually becomes zero. The injection-saturation problem would become even more serious when ILFD is operated at lower power consumption due to the worse gain condition.

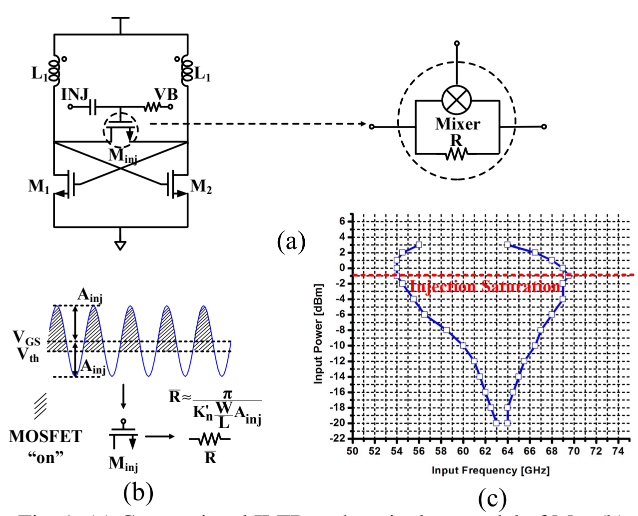


Fig. 1. (a) Conventional ILFD and equivalent model of M_{inj}, (b) injection-saturation analysis, and (c) simulated sensitivity curve.

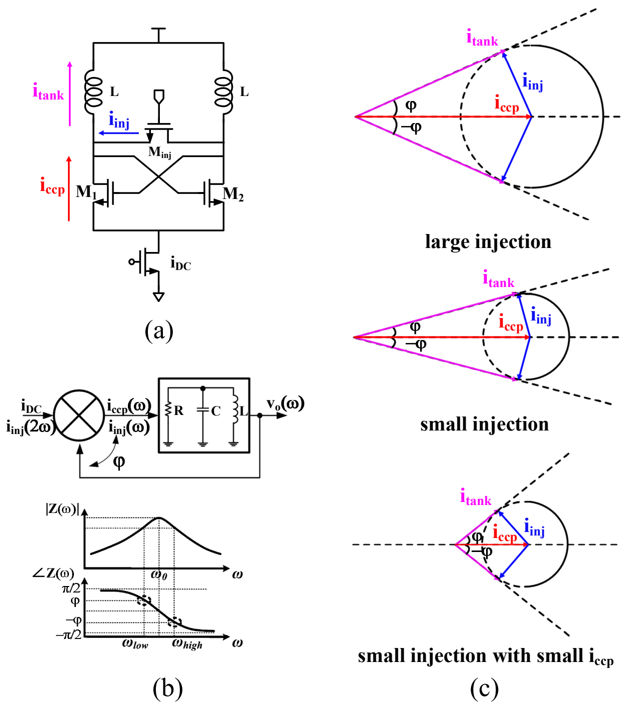


Fig. 2. Conventional ILFDs: (a) schematic, (b) behavior model, and (c) phasor diagram.

III. PROPOSED ULTRA-LOW-POWER ILFD

Fig. 2(a) and (b) show the schematic and behavior model of conventional ILFDs. To guarantee that the ILFD can meet the gain condition and suffer less from the injection-saturation problem with ultra-low power consumption, large size of cross-coupled pair M_1 and M_2 is required to provide enough negative g_m. Unfortunately, the parasitic capacitance of cross-coupled pair would dominate the total capacitance of the LC tank at MMW frequency, and large size of cross-coupled pair would decrease LR of ILFD.

Besides, conventional ILFDs are not suitable for small input power applications. As shown in Fig. 2(c), when the input power decreases, the phasor circle would shrink and phase shift φ is very small, which would decrease LR of ILFDs. One way to increase φ and thus LR is to decrease the switching current i_{ccp} from the cross-coupled pair [3] as shown in Fig. 2(c). However, as analyzed before, decreasing i_{ccp} would worsen the gain condition of conventional ILFDs, which may cause the ILFD to suffer more from the injection-saturation problem and fail to lock. As a result, to make ILFDs locked with small input power and ultra-low power consumption at MMW frequency, a new topology of ILFD is desired.

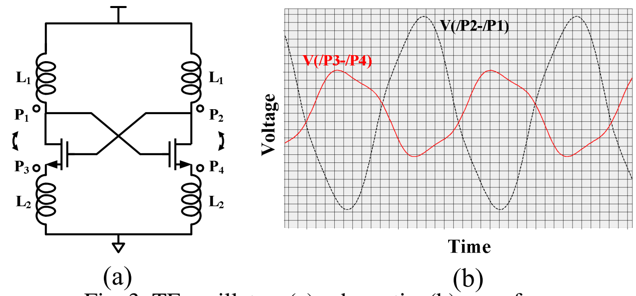


Fig. 3. TF oscillator: (a) schematic, (b) waveform.

TF technique was proposed in [1] to achieve ultra-low power consumption for VCO as shown in Fig. 3(a). The secondary coil of the transformer L_2 is connected to the source terminal of the cross-coupled pair as a feedback component. L_1 and L_2 are magnetically coupled to each other. The simulated transient waveform of the oscillator resonant at 30GHz is shown in Fig. 3(b). When the gate voltage of cross-coupled pair increases, the source voltage decreases. The out-of-phase relationship between the gate and source voltage provides extra voltage headroom and larger negative g_m according to [1], which results in better gain condition and enables the ILFD to work with a small bias current at ultra-low voltage supply. Moreover, based on the previous analysis in Fig. 2(c), ILFD based on TF technique can be locked with a relative wider locking range with smaller input power because of smaller i_{ccp}.

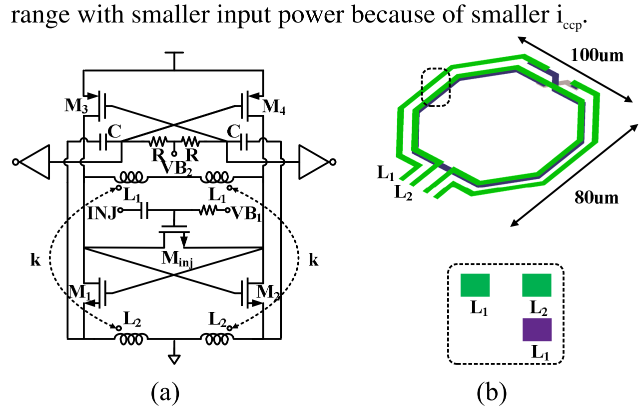


Fig. 4. Proposed ULP-ILFD: (a) schematic, and (b) stacked transformer.

To further enhance LR, the transformer is utilized not only as a feedback component to lower power consumption, but also as a component to distribute the parasitic capacitance. The proposed ULP-ILFD is shown in Fig. 4(a). The output buffer is connected to the secondary coil of transformer (L_2). Then the parasitic capacitance of buffer will be distributed to the secondary coil and thus has less loading effect on the tank. The TD topology can be analyzed as shown in Fig. 5(a). C_1 represents the capacitance of cross-coupled pair (CCP) M_1

and M_2 and the injection transistor M_{inj}, while C_2 represents the capacitance of buffer and split CCP M_3 and M_4. By replacing the transformer with T model, the equivalent schematic is similar to inductor-distribution tank in [4] as shown in Fig. 5(b). According to [4], inductor distribution helps to enhance the operation frequency and LR of ILFDs. Compared with inductor-distribution technique, the TD technique has several advantages. Firstly, by using transformer instead of inductors, the layout is more compact. Secondly, compared with inductor-distribution tank, an additional inductor L_2-M exists. The equivalent capacitance of L_2-M in series with C_2 in Fig. 5(c) can be expressed as follows:

$$C_{eq} = \frac{C_2}{1-(L_2-M)C_2\omega^2} \tag{2}$$

Note that when L_2-M is negative, C_{eq} is smaller than C_2, which will help to enhance LR due to less loading effect of capacitance. Finally, to distribute more parasitic capacitance to the secondary coil for wider LR, the cross-coupled pair is split as shown in Fig. 4(a). M_3 and M_4 are split from M_1 and M_2 and their gate terminals are connected to the secondary coil L_2. R and C are used for AC coupling and biasing M_3 and M_4. Together with the transformer tank, M_3 and M_4 form a two-port oscillator. To further lower power consumption, M_3 and M_4 are designed as PMOS transistors for current reuse.

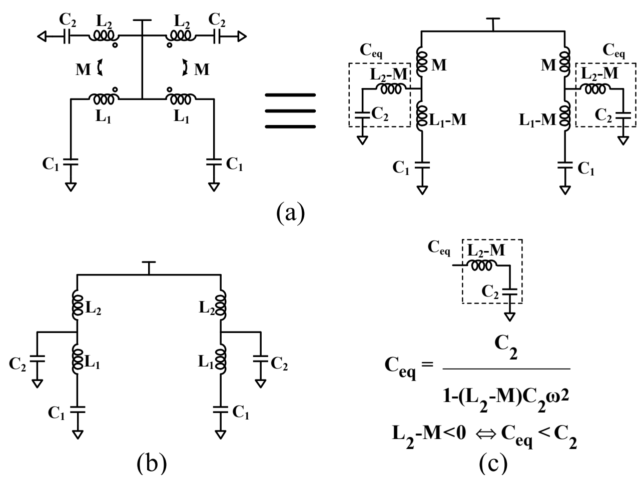


Fig. 5. (a) TD tank and equivalent circuit, (b) inductor-distribution tank, and (c) equivalent loading capacitance.

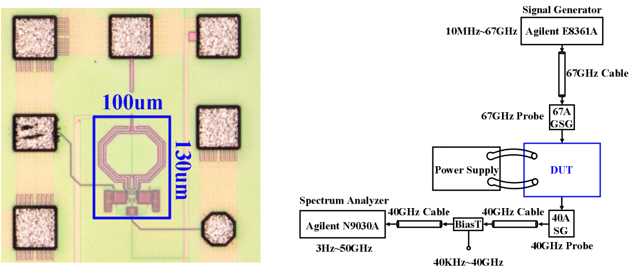
Considering TF topology, a transformer with a large coupling factor k is desired to enhance the feedback voltage swing and thus the negative gm. For TD topology, a larger k is also desired because larger mutual coupling M will bring back more negative L_2-M, which will help to decrease the loading effect of C_2 according to Eq. (2). As a result, considering both TF and TD, a larger mutual coupling of transformer is desired. To enhance the mutual coupling of transformer at MMW frequency, a stacked transformer is designed as shown in Fig. 4(b). Primary coil L_1 has two turns while secondary coil L_2 has only one turn. The first turn of L_1 is laid out using M9 while the second turn is laid out using M8 right below L_2 (using M9) for more mutual coupling. According to EM simulation result, the coupling factor k of transformer is 0.7 at 30GHz, while L_1 and L_2 equal to 300pH and 100pH respectively, which creates a L_2-M of -20pH for less loading effect.

IV. MEASUREMENT RESULT

The proposed ULP-ILFD is fabricated in a 65nm 1P9M GP CMOS process. The die photo is shown in Fig. 6(a). The core area is 100um x 130um. The layout is quite compact due to use of transformer. Fig. 6(b) shows the measurement setup. A signal generator up to 67GHz is used to provide the input and a spectrum analyzer up to 50GHz is used to measure the output of ILFD directly.

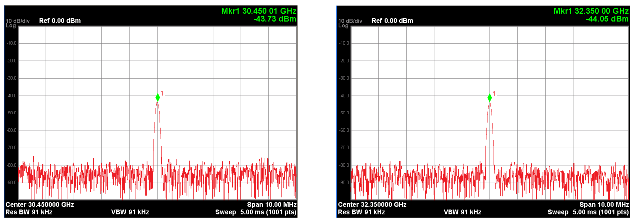
Fig. 7 shows the output spectrum when the ILFD works at ultra-low-power (ULP) mode. The ILFD draws 0.52mA current from a 0.85V supply. The measured LR is from 60.9GHz to 64.7GHz with -7dBm input power which corresponds to a FoM of 8.64GHz/mW when VB of injection transistor is biased at 0.8V. The input sensitivity curve with different bias conditions is shown in Fig. 8(a) and the plot of LR as a function of input power is shown in Fig. 8(b). Obviously, the injection-saturation phenomenon is observed. The locking range starts to be saturated when the input power exceeds certain value. It is interesting to note that when V_B decreases, the sensitivity curve moves up, and the injection-saturation problem is less. This is consistent with previous analysis because when V_{GS} of injection transistor decreases, the transistor is turned off for longer time, and the average resistance R becomes larger, which improves the gain condition of ILFD and alleviates the injection-saturation problem.

The proposed ILFD can also work in wide-locking-range (WLR) mode. When V_{DD} is increased to 1V and current is increased to 1mA, the measured LR is from 57.2GHz to 66.9GHz with -1dBm input power, corresponding to a FoM of 9.7GHz/mW. The output spectrum is shown in Fig. 9. The input sensitivity curve and LR as a function of input power is shown in Fig. 10. The injection-saturation phenomenon is still clearly observed. However, LR isn't saturated until the input power increases to -1dBm because larger power consumption helps to improve the gain condition of ILFD, which is also consistent with previous analysis. Performance summary is shown in Table I.



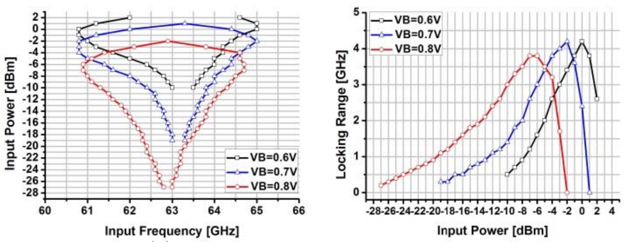
(a) (b)

Fig. 6. (a) Die photo, and (b) measurement setup.



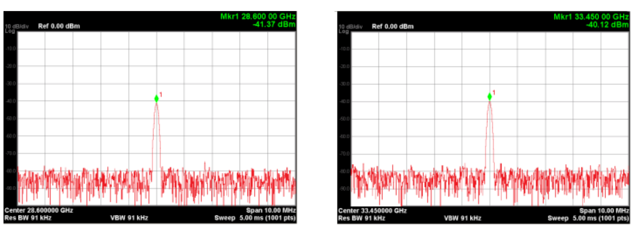
(a) (b)

Fig. 7. Output spectrum locked at: (a) 60.9GHz, and (b) 64.7GHz.



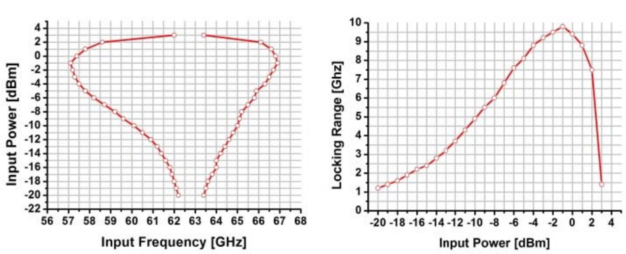
(a) (b)

Fig. 8. Measurements at 0.85V supply and 0.52mA bias current: (a) Input sensitivity curve, and (b) LR vs. input power.



(a) (b)

Fig. 9. Output spectrum locked at: (a) 57.2GHz, and (b) 66.9GHz.



(a) (b)

Fig. 10. Measurements at 1V supply and 1mA bias current: (a) Input sensitivity curve, and (b) LR vs. input power.

Table I. Measured performance summary and comparison

Ref. ILFD	[2]	[3]	[5]	This work	
				ULP	WLR
Frequency [GHz]	66.4	63.3	55.7	62.6	62.1
Input Power [dBm]	0	0	0	**-7**	**-1**
Locking Range [GHz, %]	26 (39.2%)	7.4 (11.7%)	14.4 (25.9)	3.8 (6.1%)	9.7 (15.6 %)
Power [uW]	2900	1600	1650	440	1000
Vdd [V]	0.8	0.8	1.1	0.85	1
FoM* [GHz/mW]	8.97	4.63	8.73	8.64	9.70
Area [mm^2]	0.126	0.017	0.48	0.013	0.013
Process	65nm CMOS	130nm CMOS	65nm CMOS	65nm CMOS	65nm CMOS

*FoM=(Locking Range)/(Power) [GHz/mW]

V. CONCLUSION

An injection-saturation problem with ILFDs was described and verified, based on which an ULP-ILFD was designed and demonstrated in a 65nm CMOS process. The proposed ILFD measures a LR from 60.9GHz to 64.7GHz while consuming only 440uW, which features the minimum power consumption among all the V-band frequency dividers to the best of the authors' knowledge.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support by the Hong Kong General Research Funding GRF 617609.

REFERENCES

[1] K. Kwok, et al, "Ultra-Low-Voltage High-Performance VCO Using Transformer Feedback," *IEEE Journal of Solid-State Circuits,* Vol. 40, pp. 652-660, March 2005.

[2] Y. Chao, et al, "A 2.9mW 53.4-79.4GHz Frequency-Tracking Injection-Locked Frequency Divider with 39.2% Locking Range in 65nm CMOS," *IEEE RFIC,* pp. 1-4, June 2012.

[3] S. Rong, et al, "0.9mW 7GHz and 1.6mW 60GHz Frequency Dividers with Locking-Range Enhancement in 0.13um CMOS," *IEEE ISSCC,* Feb.2009, pp. 96-97.

[4] K.-H. Tsai, et al, "3.5mW W-Band Frequency Divider with Wide Locking Range in 90nm CMOS Technology," *IEEE ISSCC,* Feb., 2008, pp. 466-467.

[5] Shibasaki, et al, "A 60-GHz 1.65mW 25.9% Locking Range Multi-Order LC Oscillator Based Injection Locked Frequency Divider in 65nm CMOS," *IEEE CICC,* Sept.2010.