A Dual-Step-Mixing ILFD using a Direct Injection Technique for High-Order Division Ratios in 60GHz Applications

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Outline

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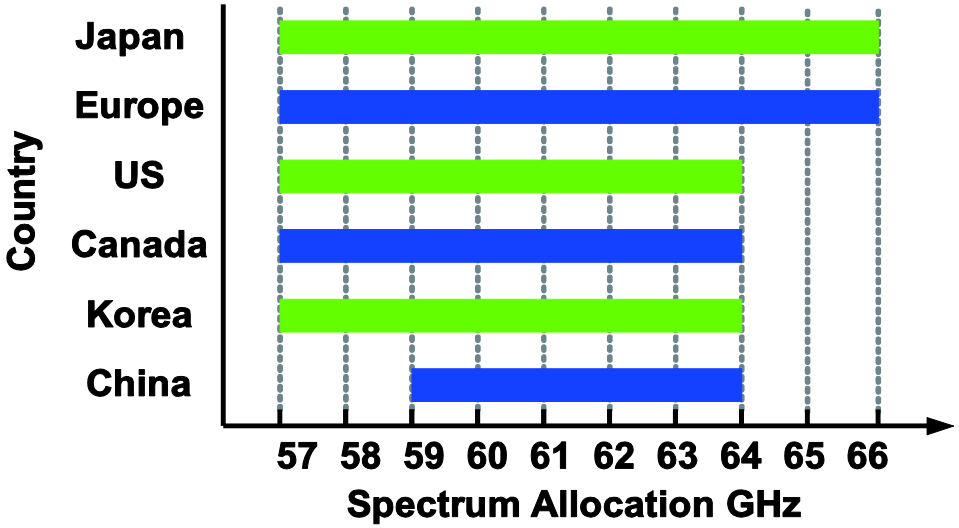
- Motivation
- Conventional ILFDs
- Proposed Dual-Step-Mixing ILFD using a Direct Injection Technique
- Performance Comparison
- Frequency Drift over PVT variations
- Integration with 20GHz PLL
- Conclusion

Background

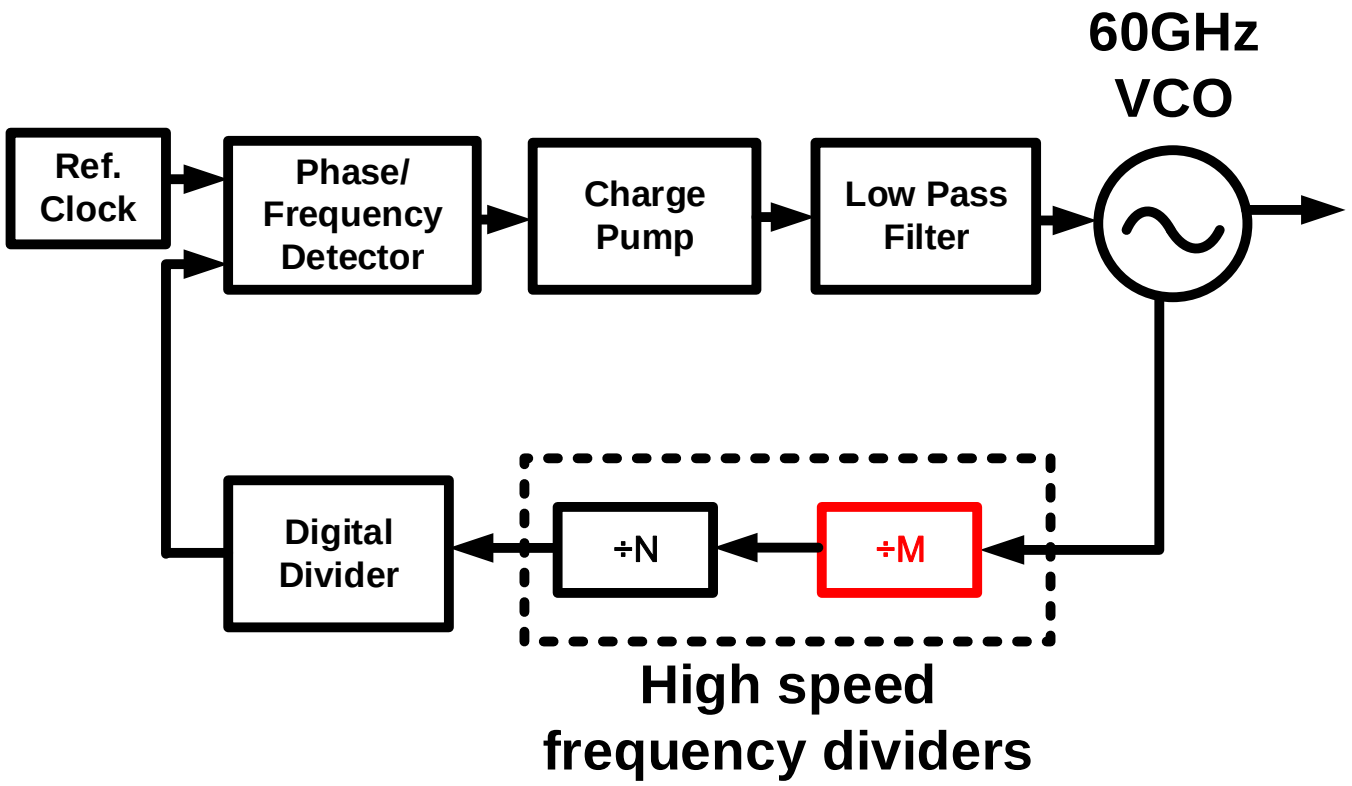
- 9-GHz unlicensed bandwidth at 60 GHz
- Several Gbps wireless communication



IEEE 802.11ad/WiGig | IEEE 802.15.3c | Wireless HD | ECMA-387 | ISO/IEC13156

[1] http://www.tele.soumu.go.jp

Direct 60GHz Frequency Synthesizer



- Direct 60GHz VCO suffers from inferior phase noise due to Q of tank at 60GHz
- Power-hungry frequency divider is required

60GHz Frequency Synthesizers

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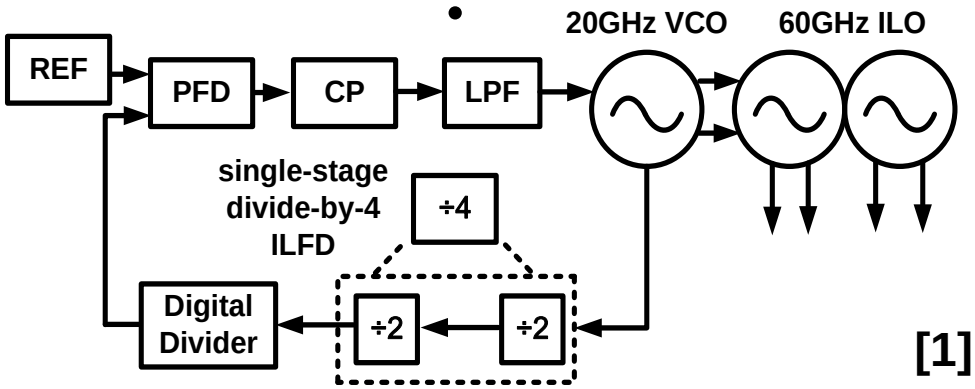
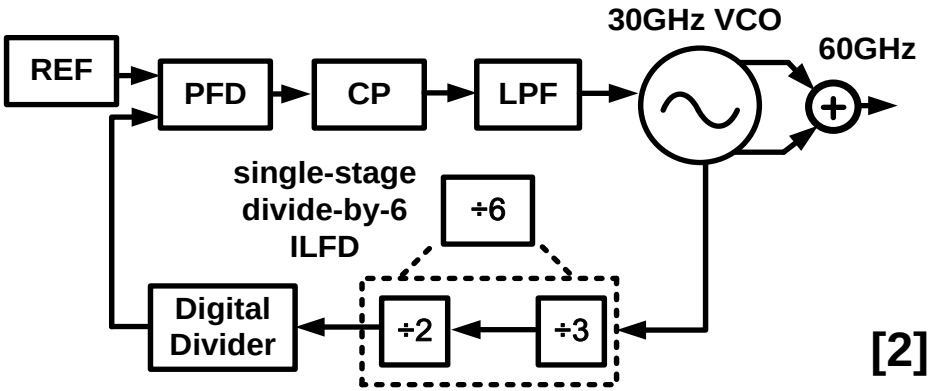
■ Sub-harmonic injection



❑ 2 divide-by-2 CML divider consumes 15mW (40% of PLL)

[1] A. Musa, *et al.*, JSSC 2011

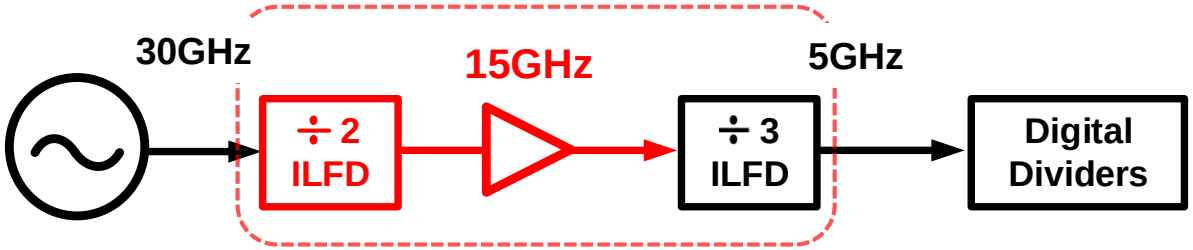
■ 60GHz push-push VCO



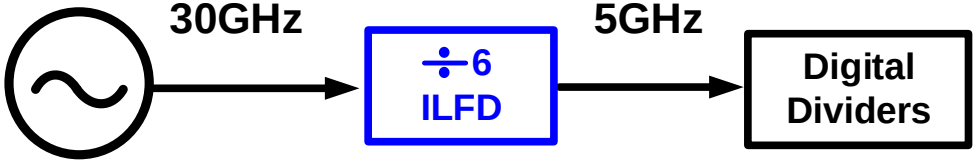
❑ Divide-by-3 ILFD + divider chain consumes more than 50% of PLL

[2] T. Tsukizawa, *et al.*, ISSCC 2013

High-speed Ring ILFD chains



- Large power
- Locking range mismatch



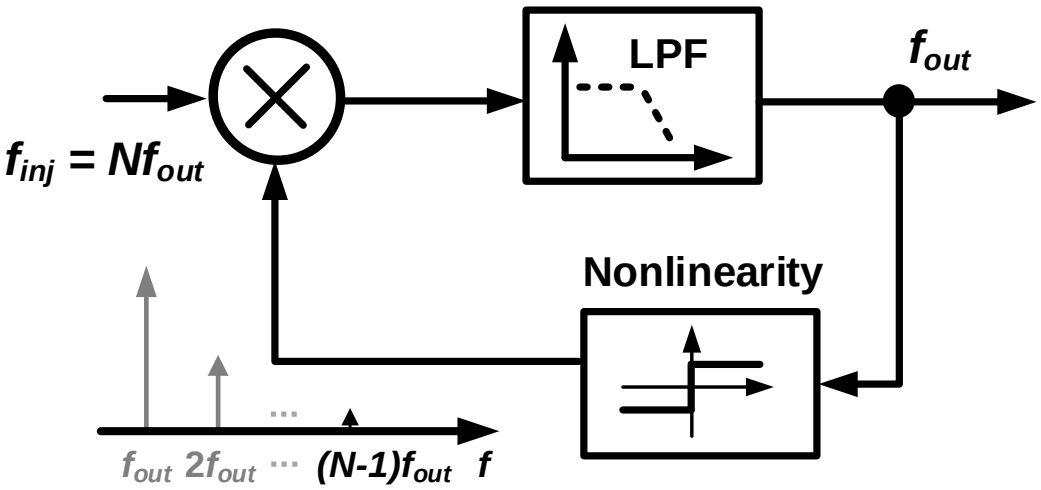
- Narrow locking range

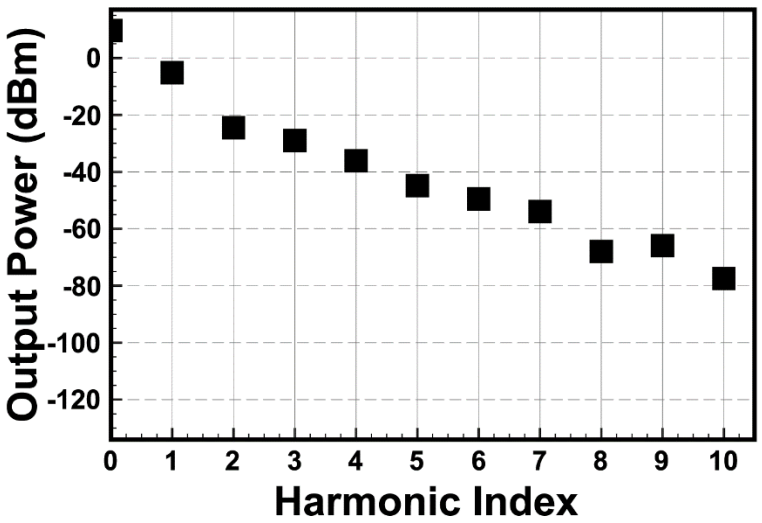
20-GHz PLL needs a divide-by-4 ILFD

30-GHz PLL needs a divide-by-6 ILFD

- **A technique to increase locking range of high-order-division in ILFDs is necessary**

Conventional Direct Mixing Ring ILFD

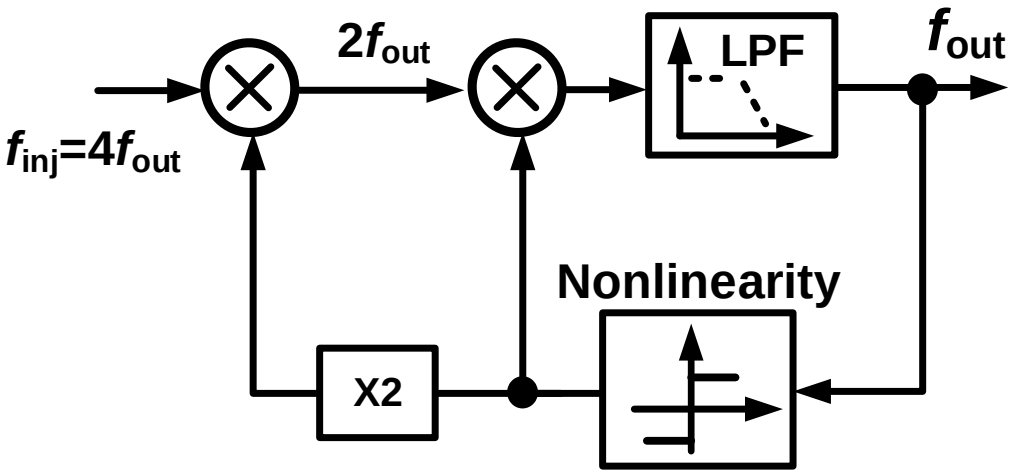


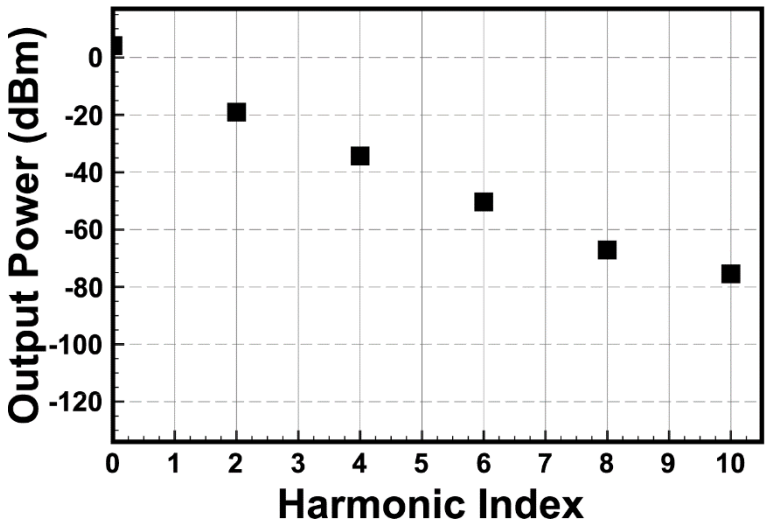


Divide by N directly in one step

- **Injection signal is directly divide by N**
- **Low power consumption**
- **Narrow Locking range**

Progressive Mixing Ring ILFD (I)



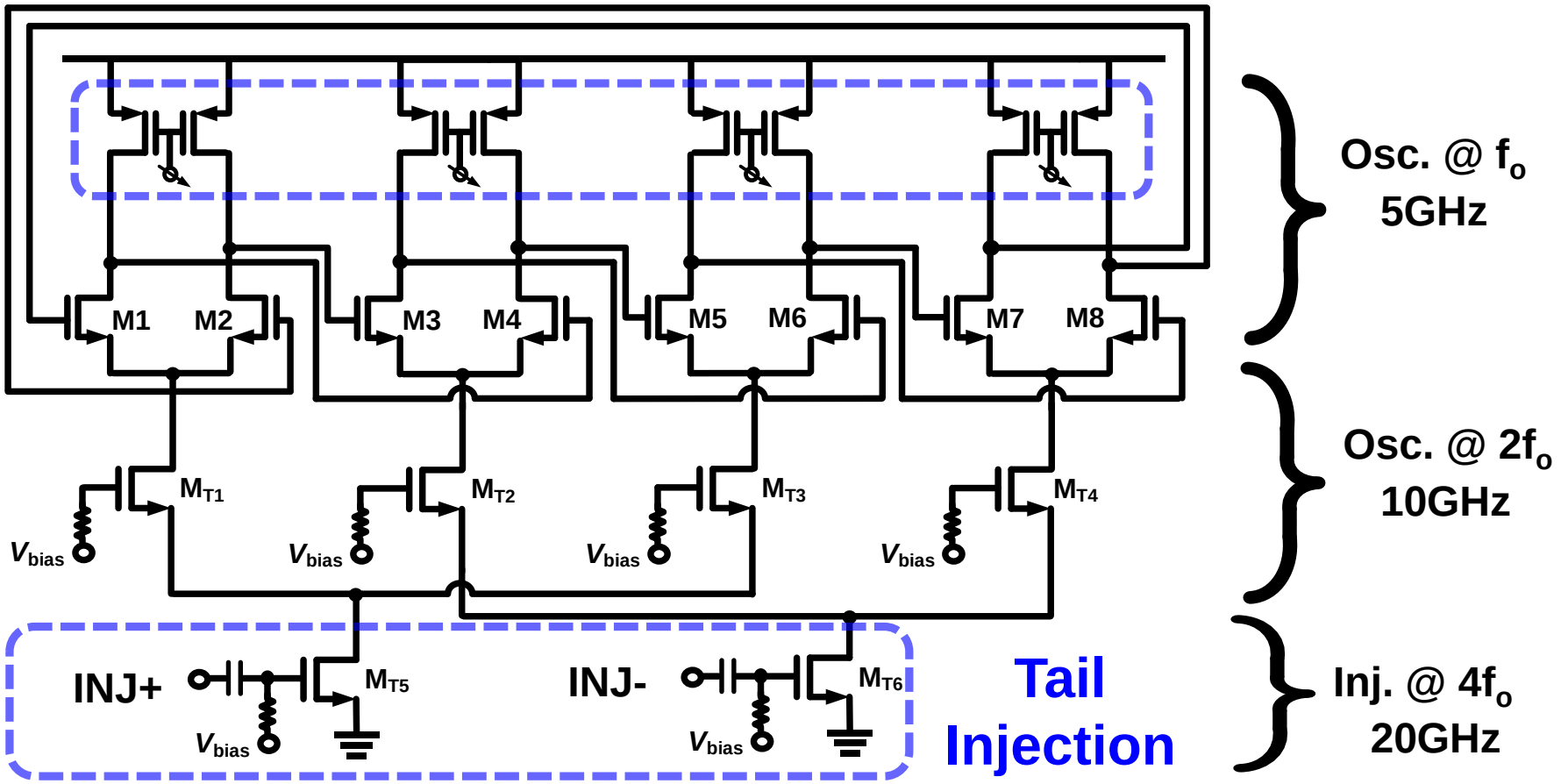


- Multi-step mixing mechanism divide-by-2^n operation, *e.g.*, 2, and 4
- Locking range is enhanced through the use of stronger harmonics

[3] A. Musa, *et al.*, A-SSCC 2011

Progressive Mixing Ring ILFD (II)

- High division ratio ILFD by reusing higher harmonic in cascoded configuration



[3] A. Musa, *et al.*, A-SSCC 2011

Issues of Conventional PMILFD (I)

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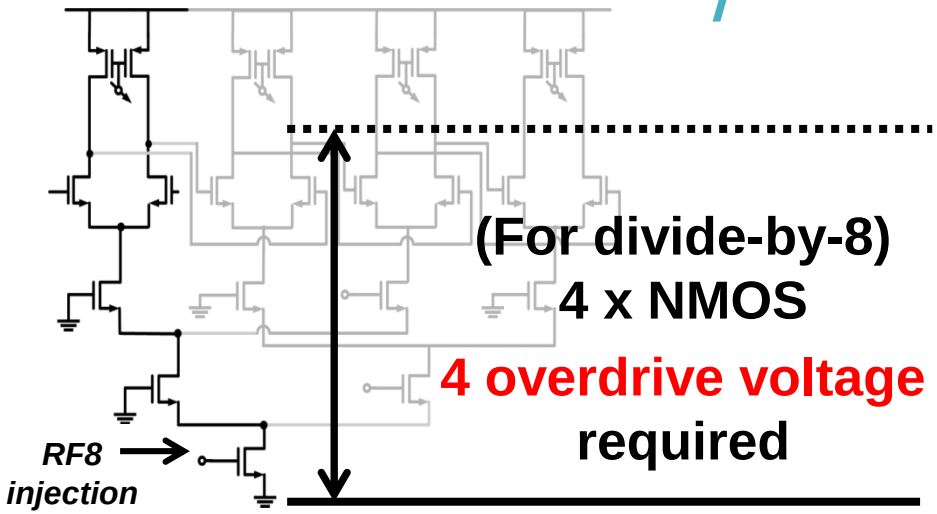
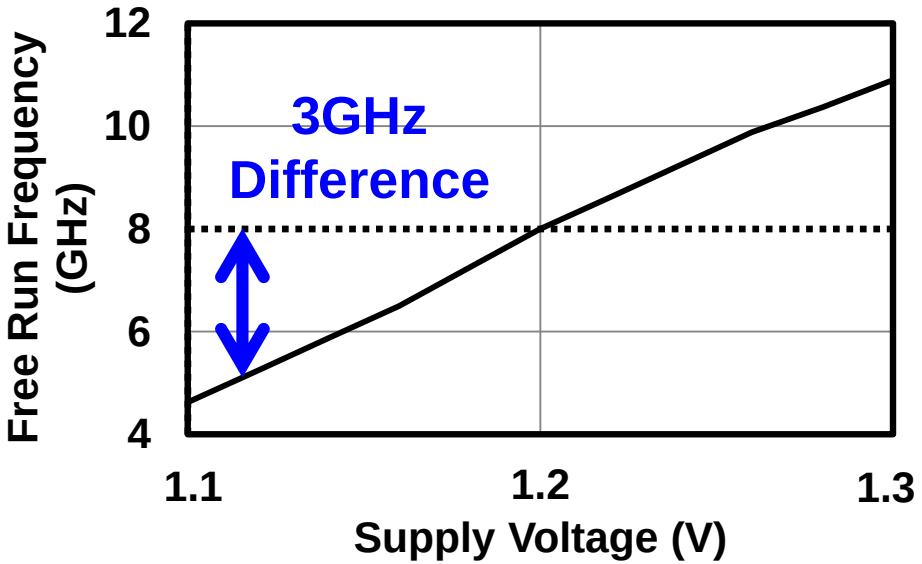
- **Large headroom**
  - — Impractical for low voltage design
  - — For 1.2 V supply, higher than 8 division is hard to be achieved



- **Sensitive to PVT due to PMOS tuning**
  - — ±10% supply pushing leads to a drift of free running frequency



Issues of Conventional PMILFD (II)

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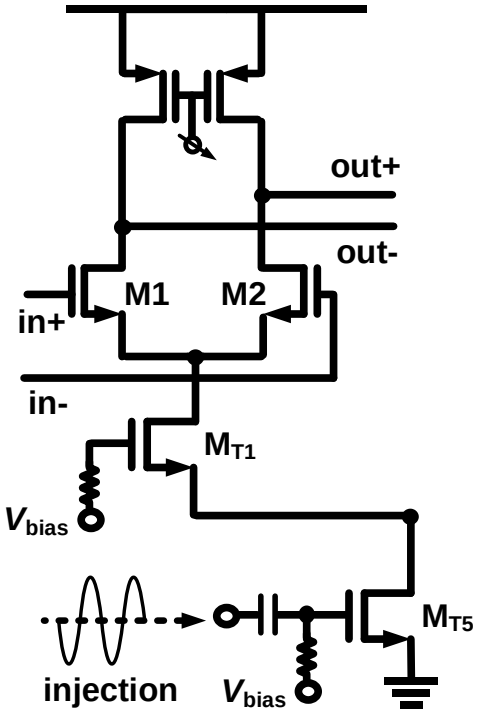
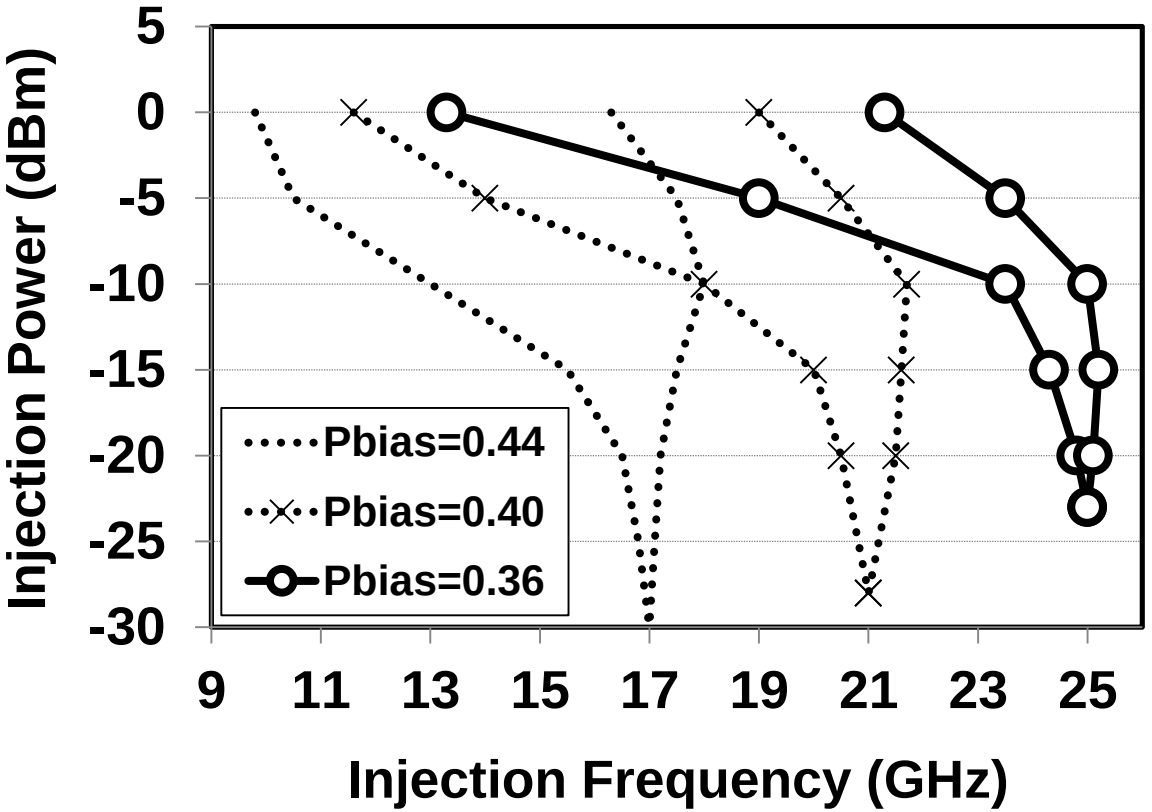
■ Asymmetric Locking Range

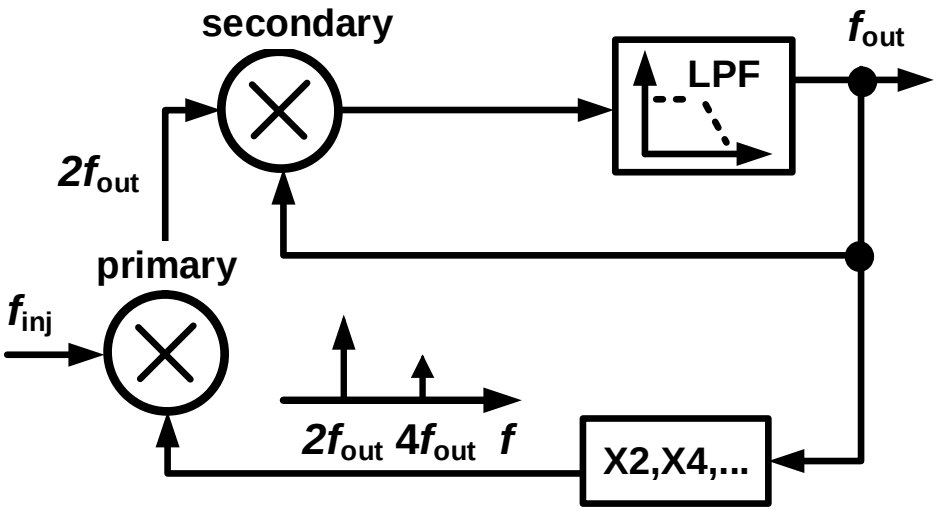


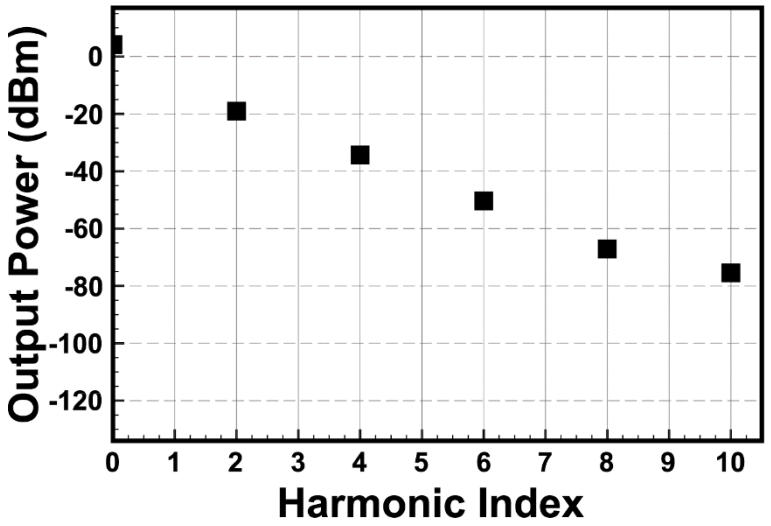


Intrinsic free-running frequency of ILFD is sensitive to large injection signal

Matsuzawa & Okada Lab.

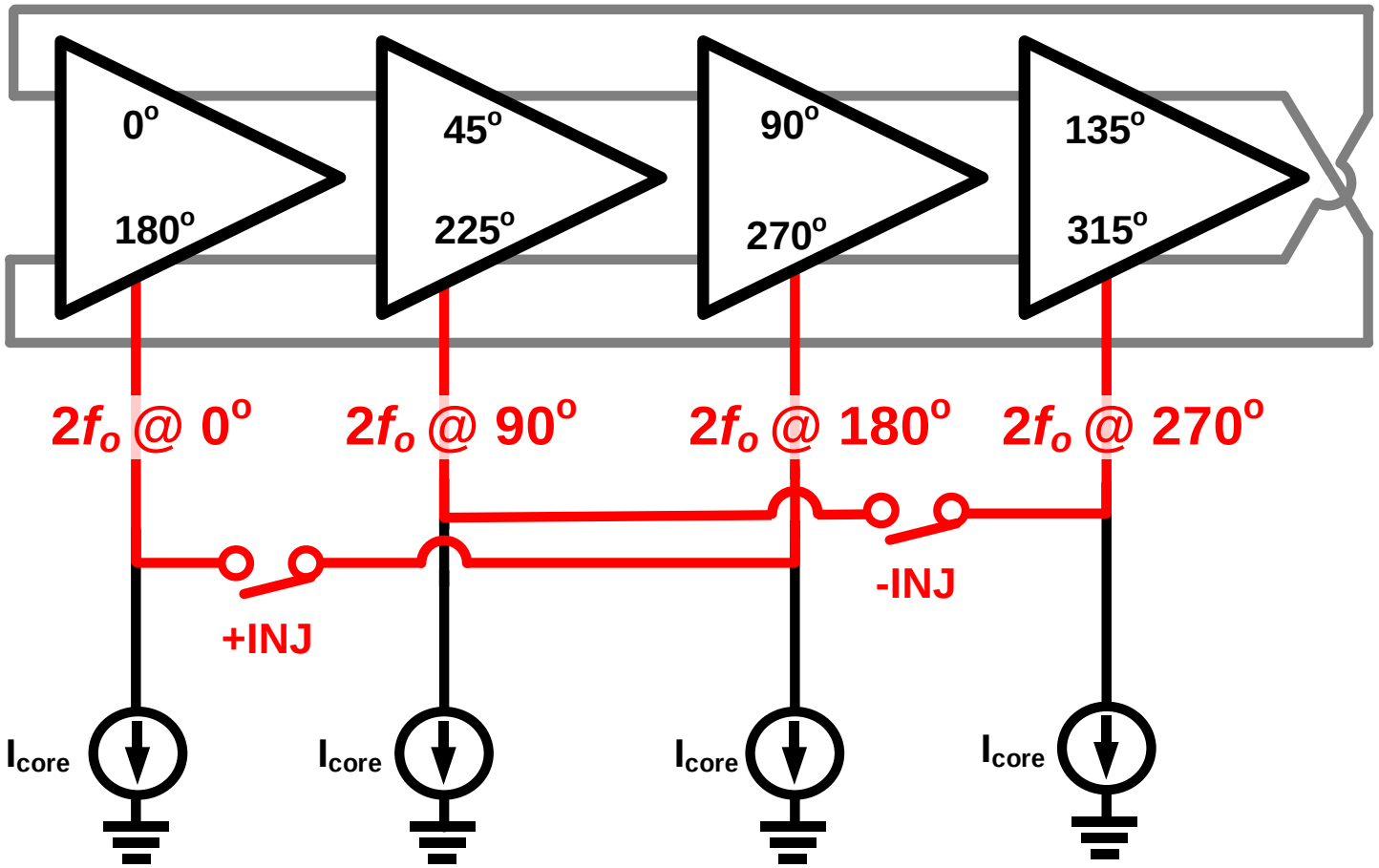
Dual-Step Mixing using Direct Injection





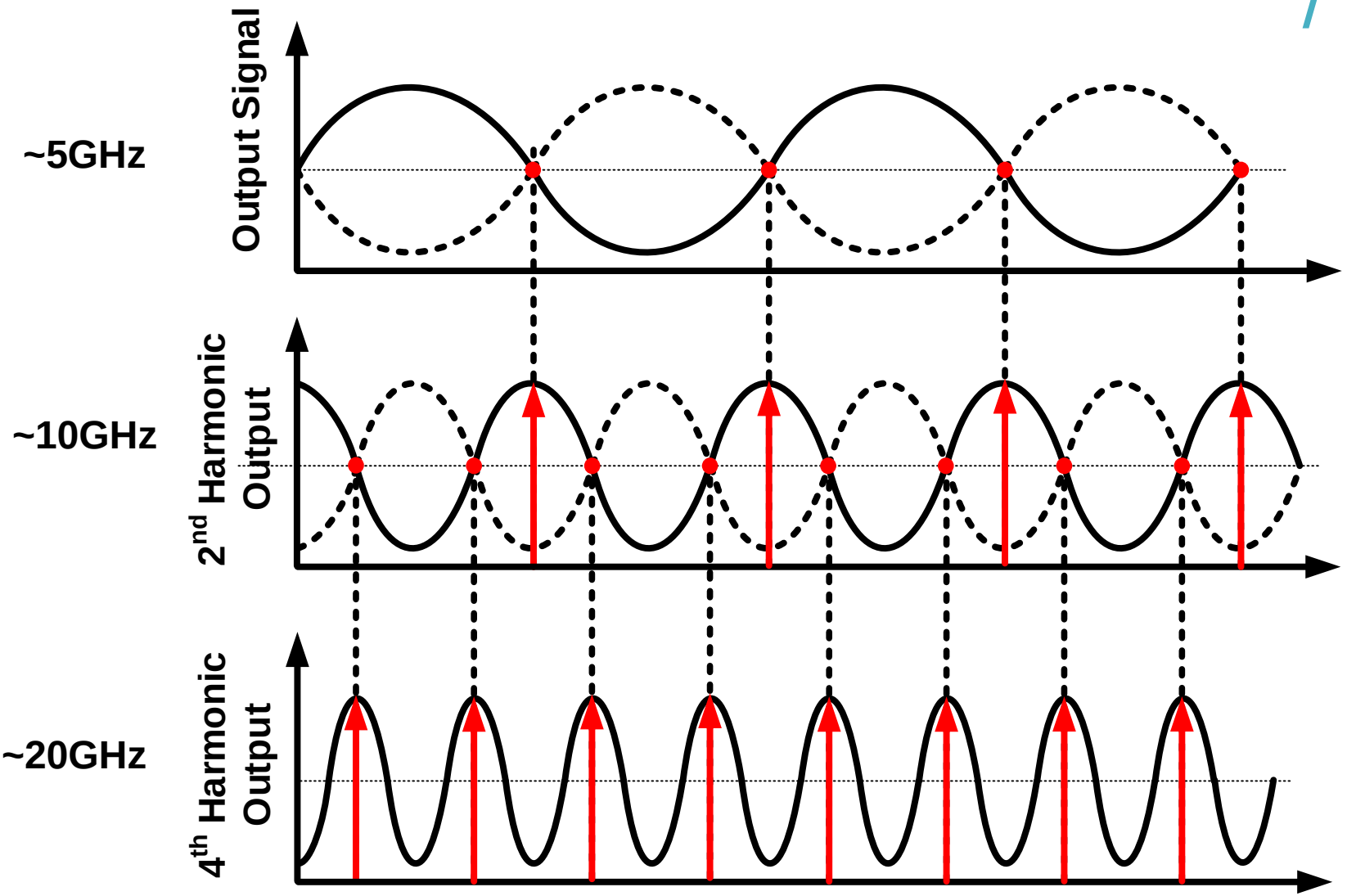
- **Dual-step mixing mechanism for divide-by-4 and divide-by-6 operation**

Proposed ILFD Configuration



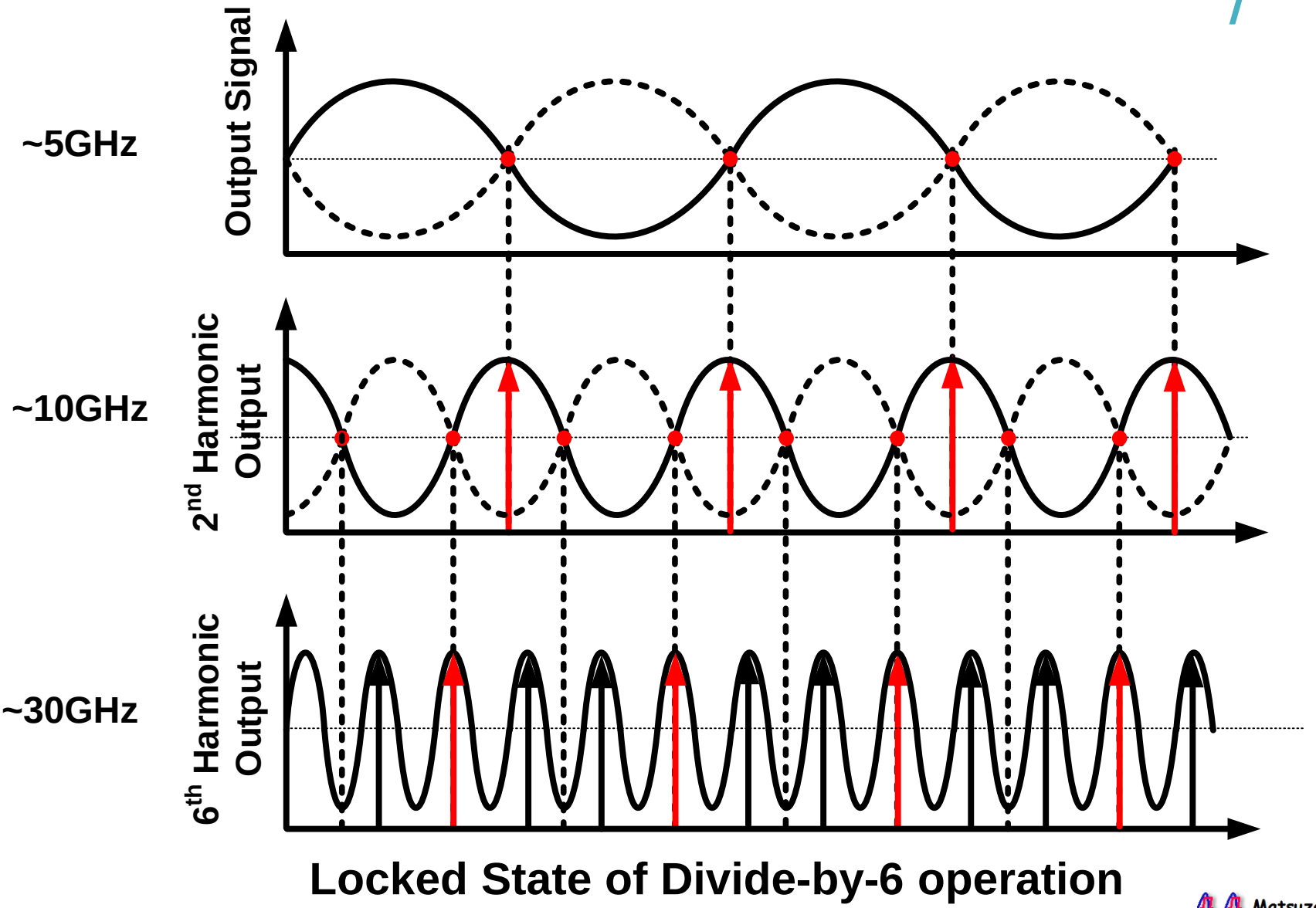
Dual-Step Mixing with Second Harmonic Direct Injection

Divide-by-4 Operation



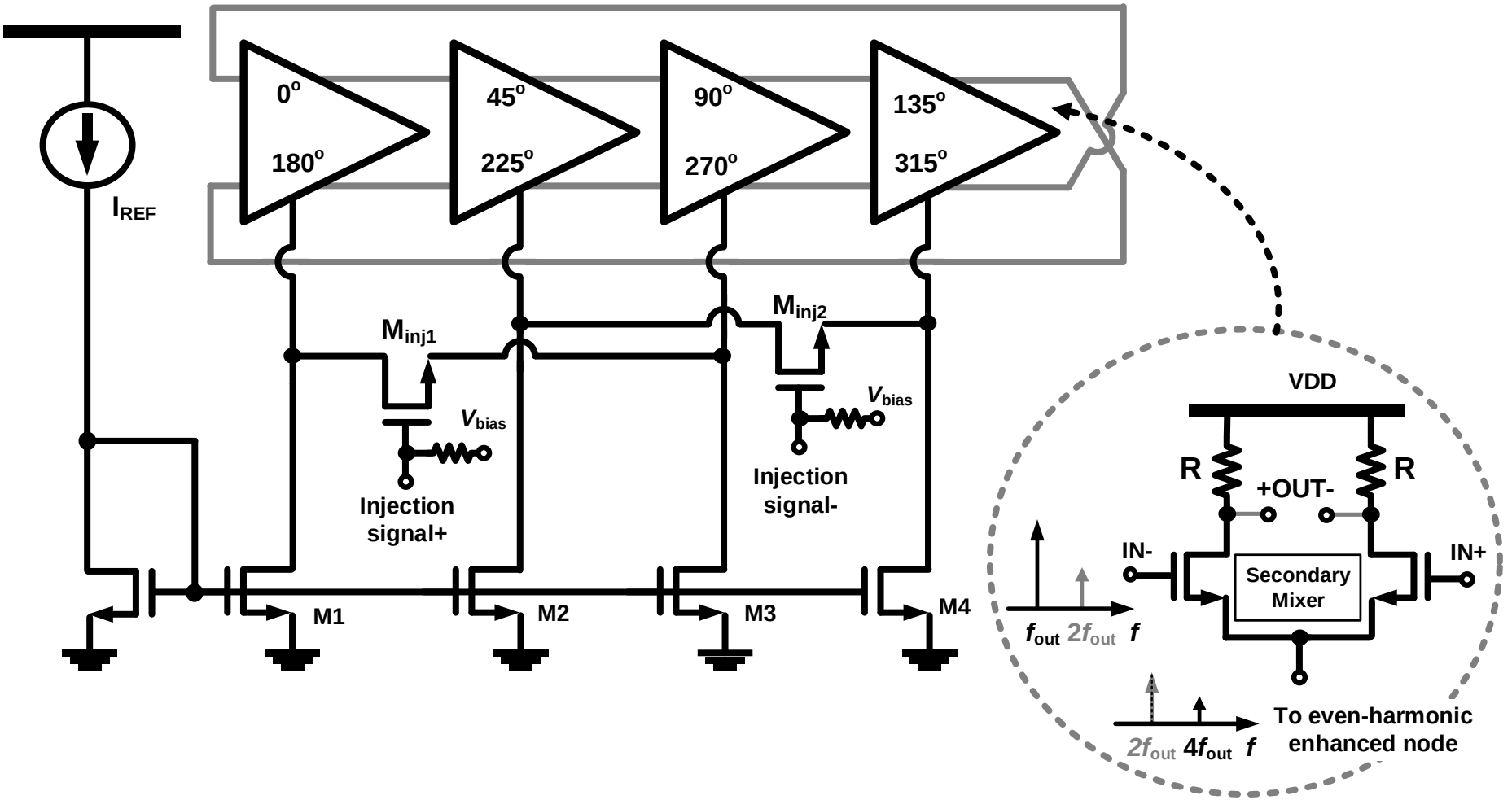
Locked State of Divide-by-4 operation

Divide-by-6 Operation



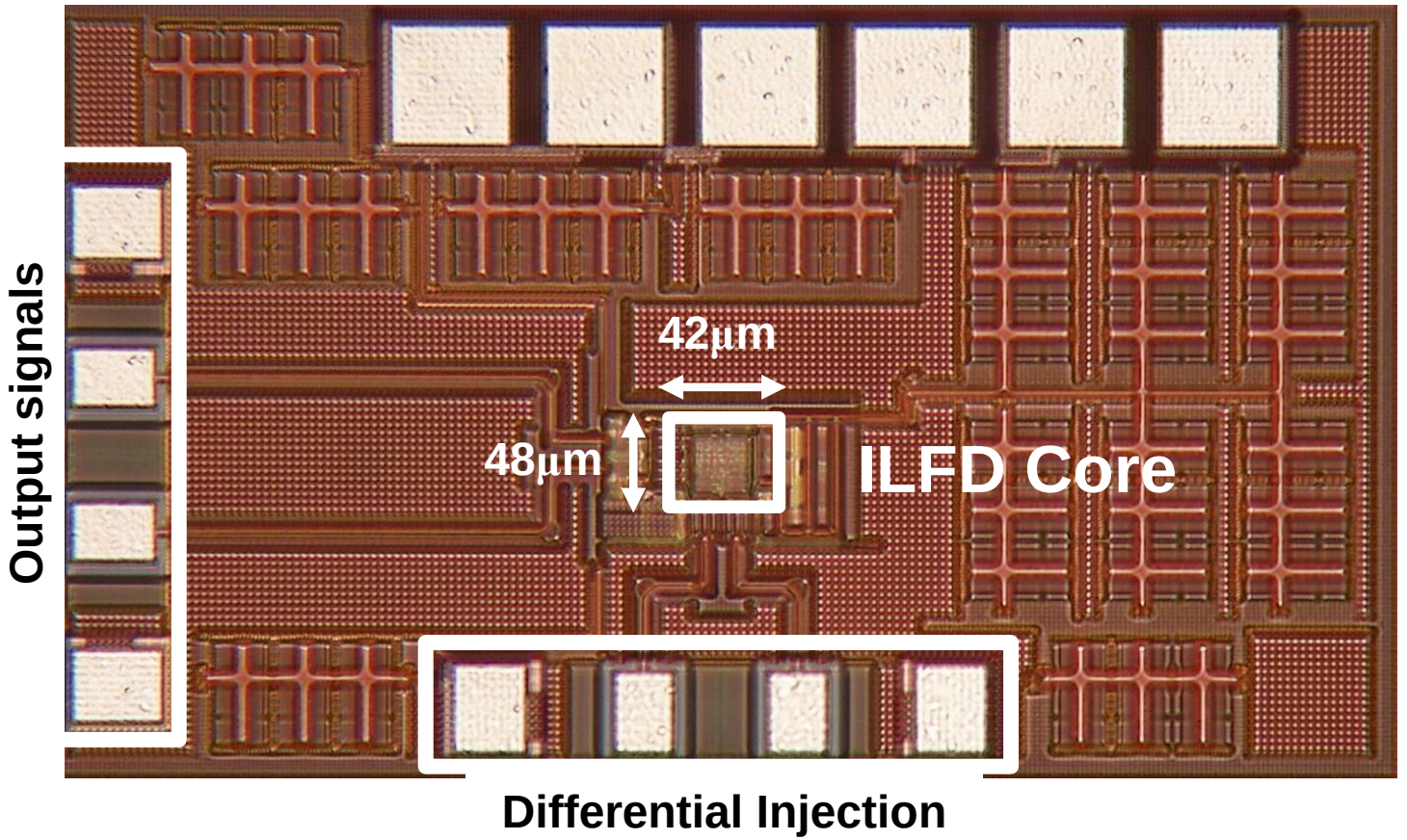
Locked State of Divide-by-6 operation

Proposed Schematic



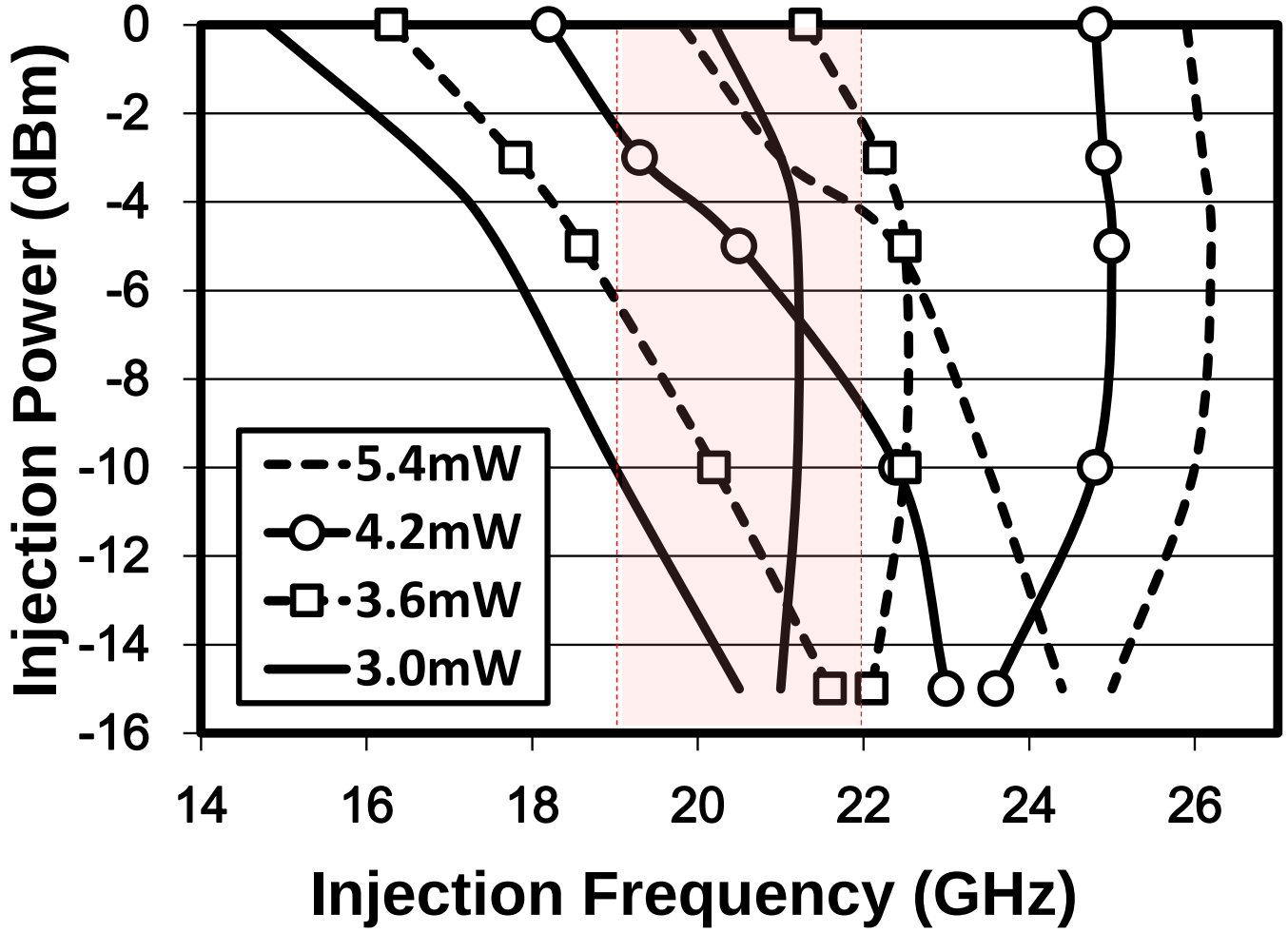
Schematic of the Proposed Dual-Step-Mixing ILFD using Even-Harmonic Direct Injection Technique

Chip Micrograph



Technology	65nm CMOS
Core area	0.002mm^2

Experimental Results for divide-by-4



Required frequency range for the 60-GHz wireless standards

Divide-by-4 Performance Comparison

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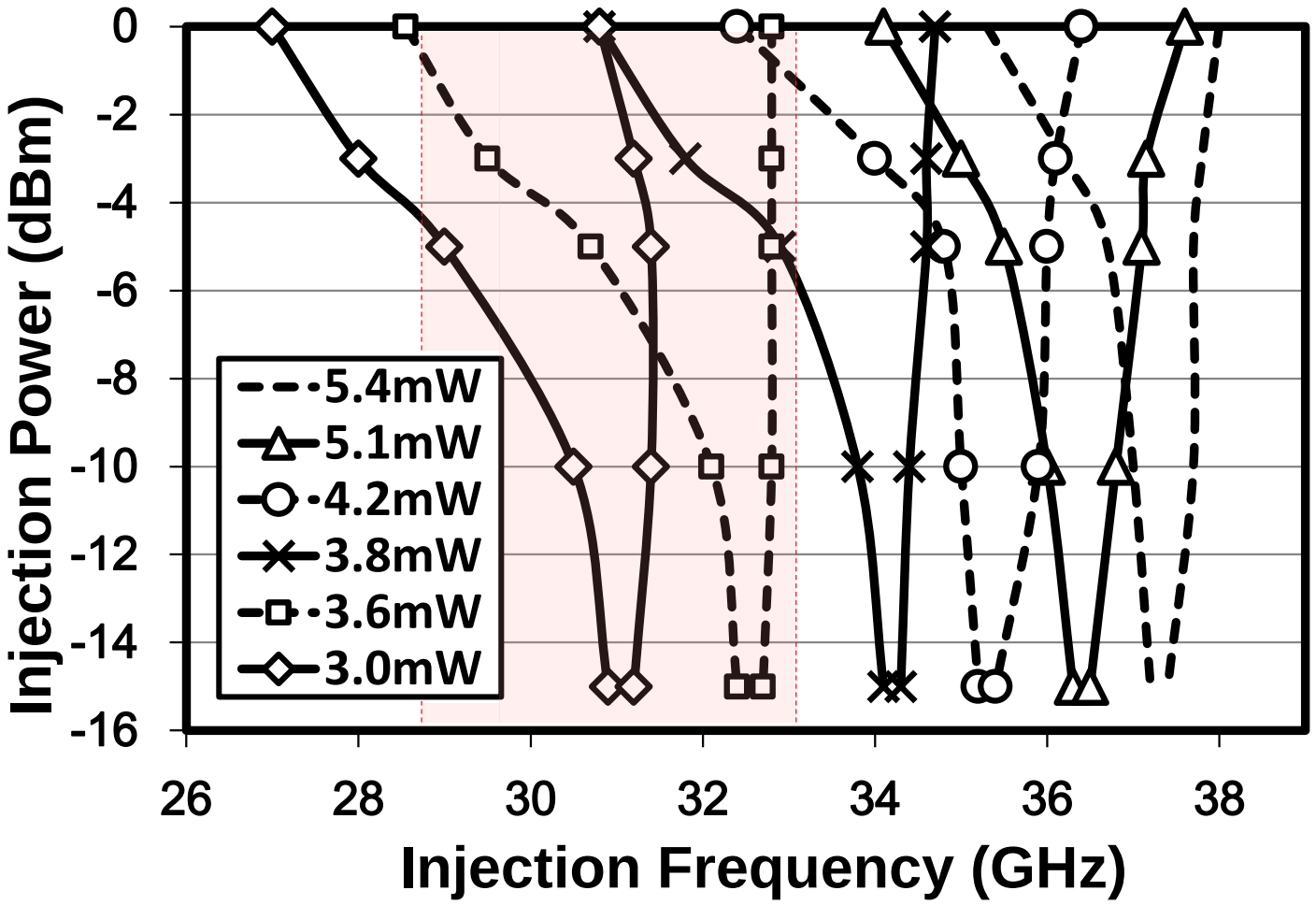
	Features	Div. Ratio	Locking Range* (GHz)	Locking Range* (%)	Power (mW)	FoM (%/mW)	Area (mm^2)
[4]	Direct mixing	4	22.6-28	21	8.3	3.5	0.140
[5]	Direct mixing	4	6.0-7.6	22	6.8	3.24	0.007
[6]	Direct mixing	4	31.0-41.0	27	3.3	8.18	0.002
[7]	LC Direct mixing	4	58.5-72.9	21.9	2.2	9.95	0.032
[8]	CML + LC ILFD	4	13.5-30.5	77.3	7.3	10.6	0.33
[9]*	Progressive mixing	4	13.4-21.3	31	3.9	7.95	0.003
This	Even-harmonic-enhanced	4	15.2-20.4	24.25	3.1	7.82	0.002

FoM=(%Lock Range)/(mW Power)

[4] A-SSCC'07 [5] RFIC'04 [6] ISSCC'06 [7] CICC'12

[8] MTT'11 [9] A-SSCC'11

Experimental Results for divide-by-6



Required frequency range for the 60-GHz wireless standards

Divide-by-6 Performance Comparison

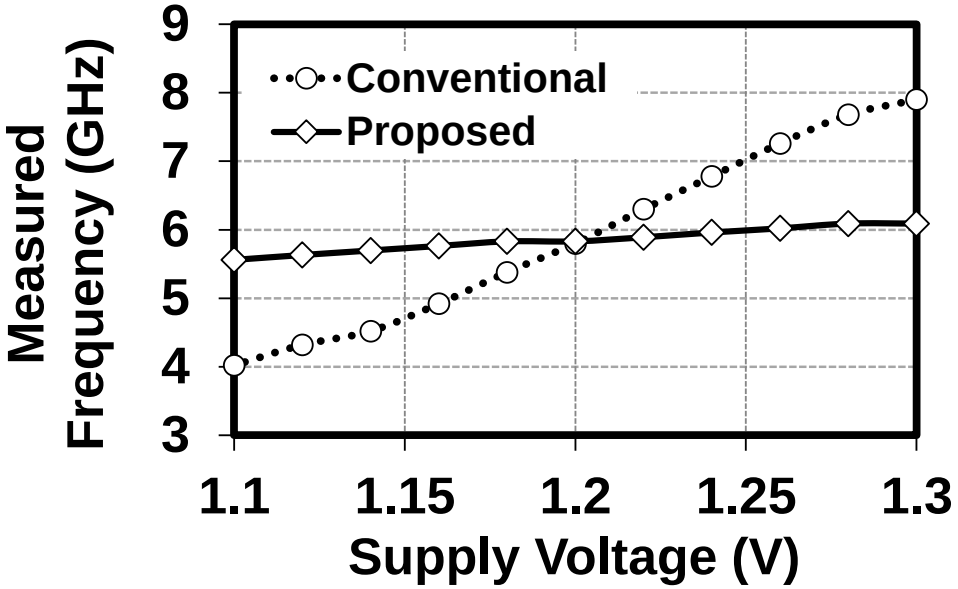
	Features	Div. Ratio	Locking Range* (GHz)	Locking Range* (%)	Power (mW)	FoM (%/mW)	Area (mm^2)
[4]	Direct mixing	3	21.7-24.9	13.7	8.3	1.7	0.140
[5]	Direct mixing	3	53.9-57.8	7.0	4.6	1.5	0.800
[6]	Direct mixing	6	141.0-144.3	2.7	14.0	0.2	1.160
[7]	Direct mixing	6	10.2-11.3	11.0	6.8	1.6	0.007
[8]	Direct mixing	6	14.6-15.4	5.0	12.5	0.4	0.300
[9]	Current reused ILFD	6	121.0-124.8	3.5	4.5	0.8	0.140
This	Even-harmonic-enhanced	6	27.7-32.0	13.2	3.1	4.0	0.002

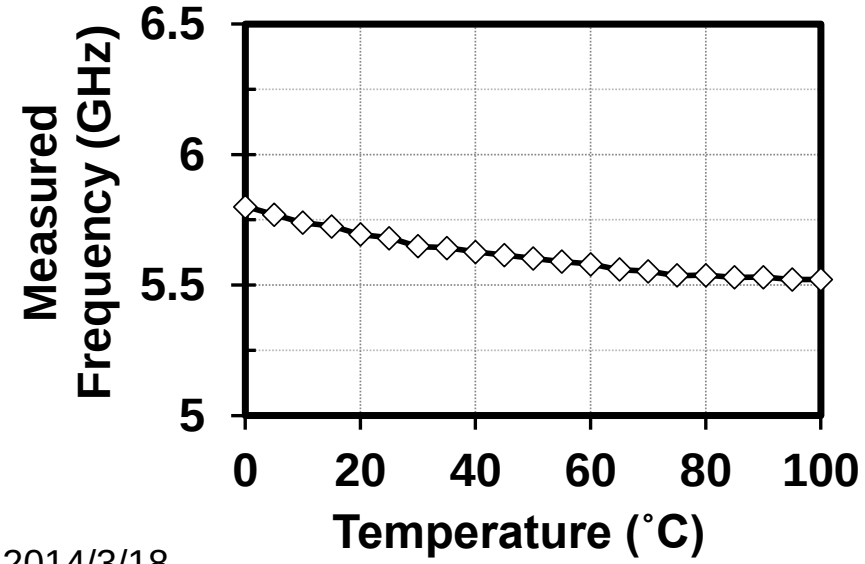
FoM = (%Lock Range)/(mW Power)

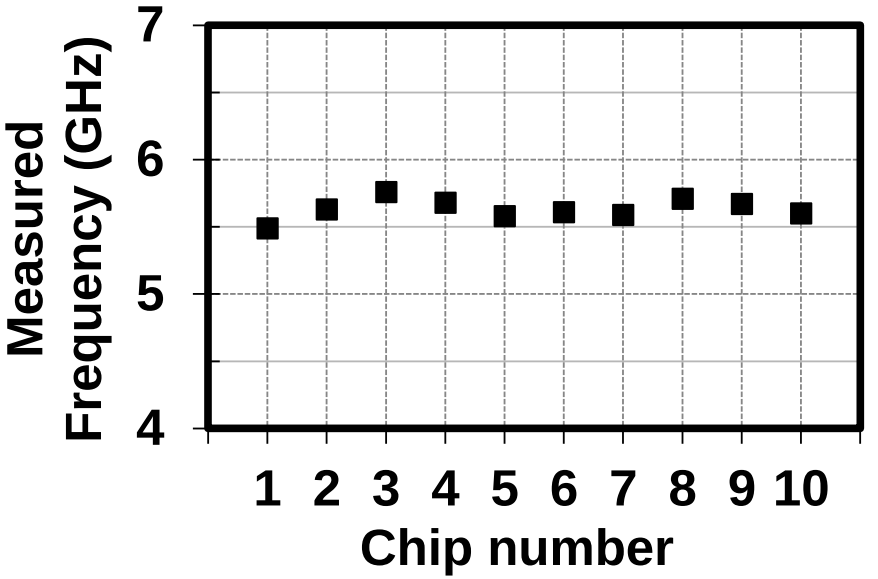
[4] MTT'12 [5] ISSCC'09 [6] A-SSCC'11 [7] RFIC'04

[8] RFIC'05 [9] MTT'13

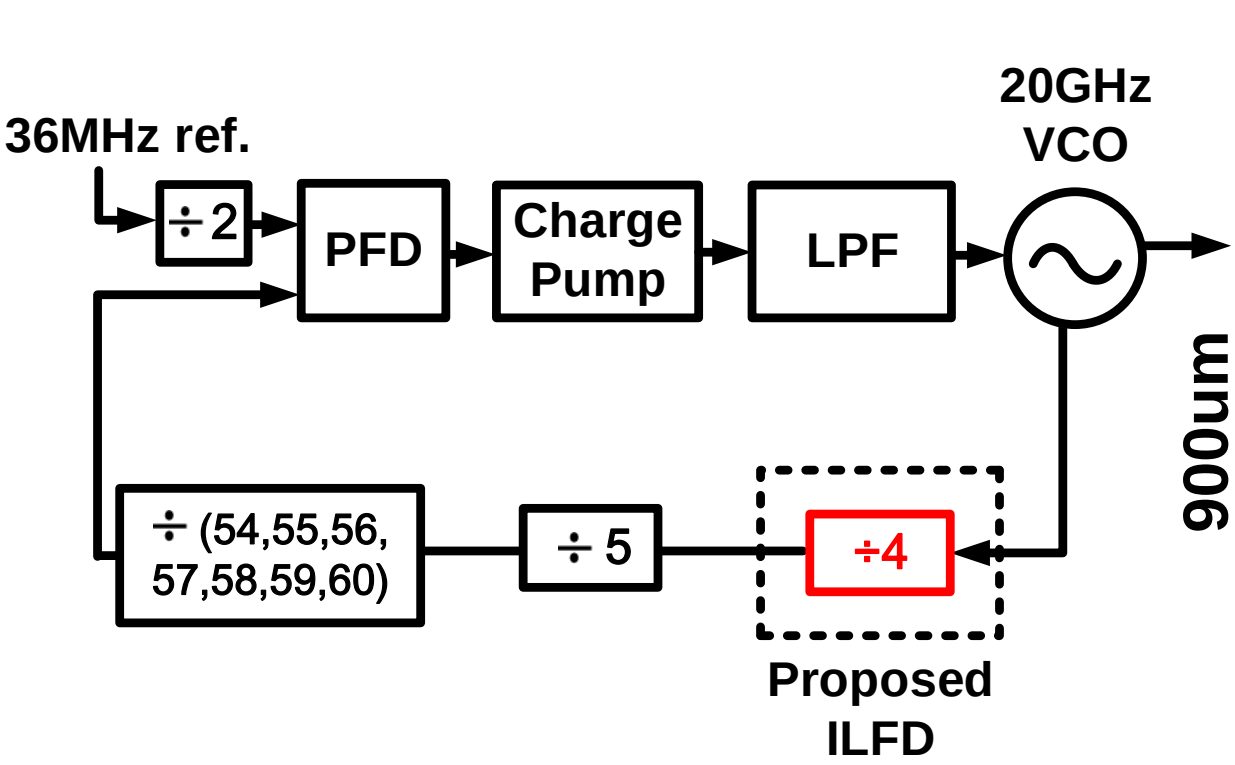
Frequency Drift over PVT variations

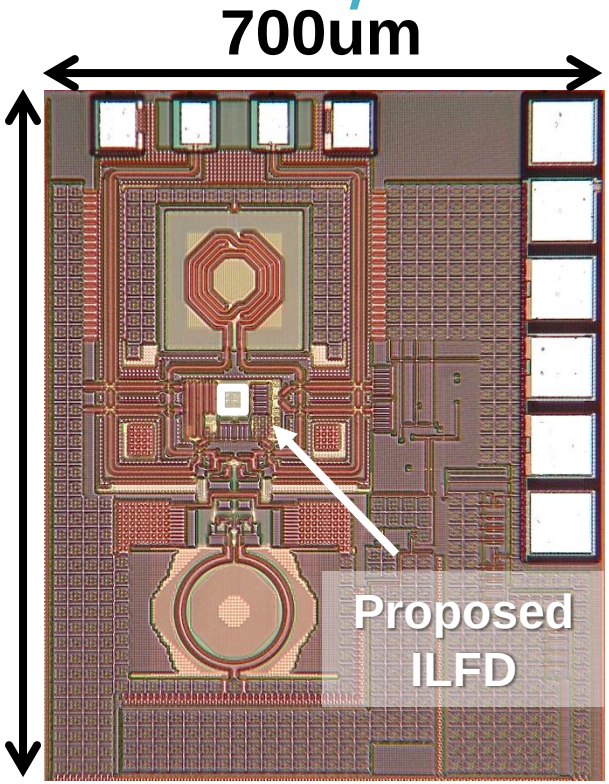






Integration with the 20GHz PLL

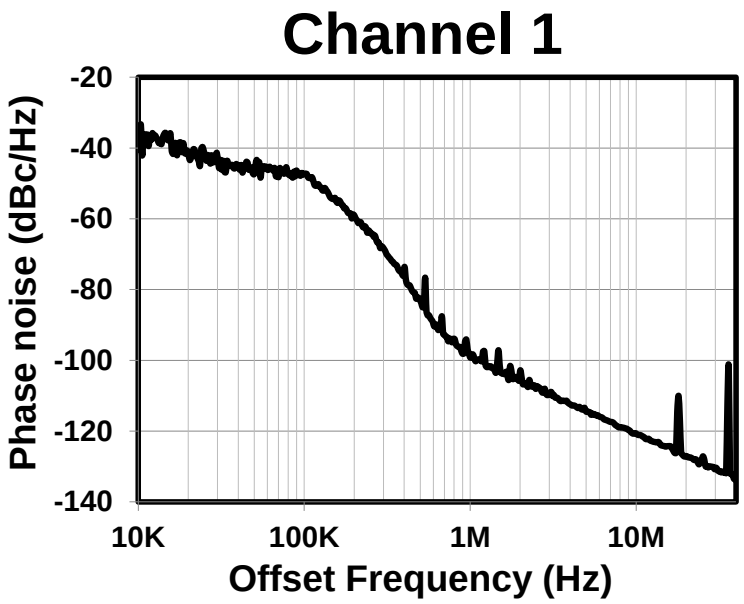


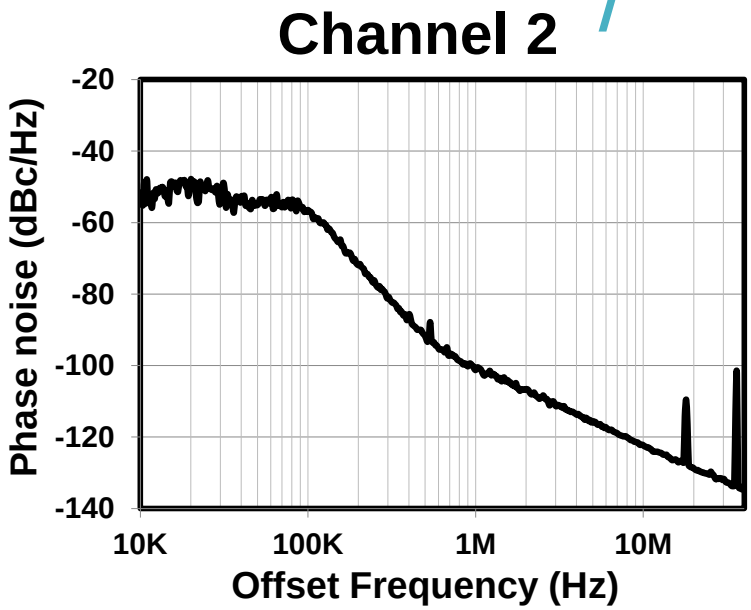


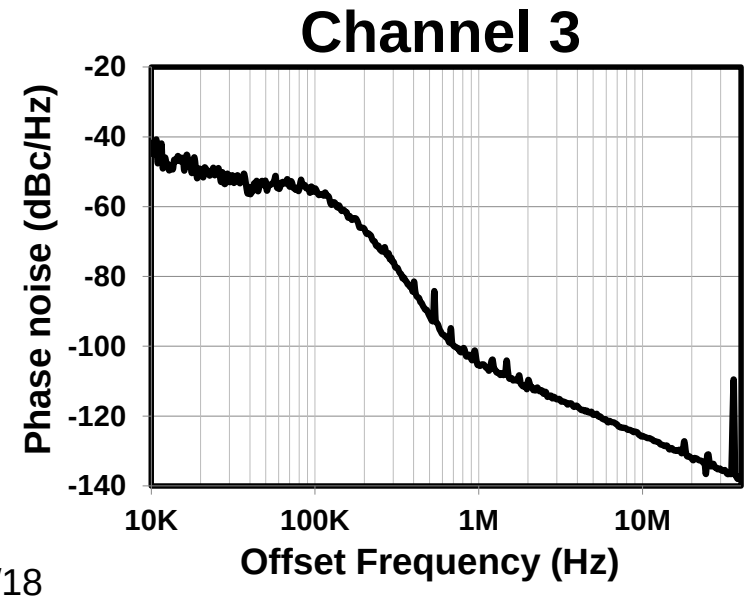
- **Proposed ILFD consumes only 4.2mW**
  (Two cascading CML dividers consumes 14mW [1])

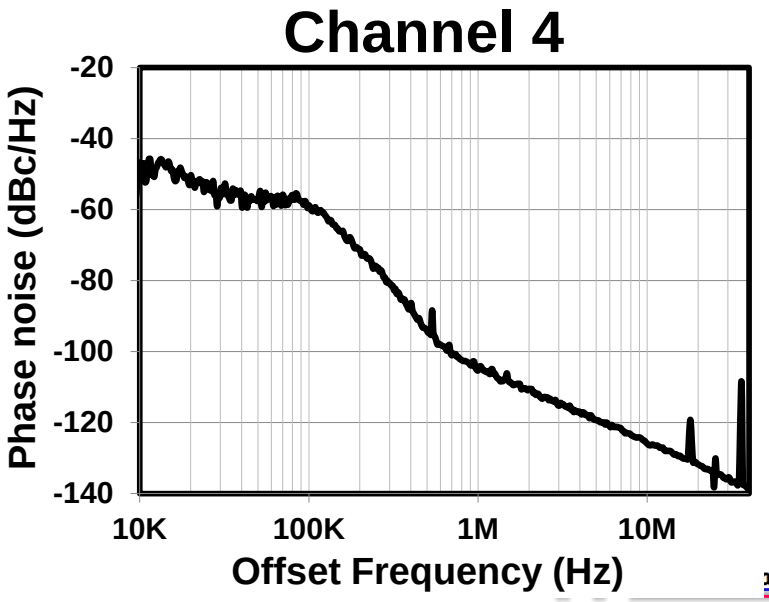
[1] K. Okada, *et al.*, JSSC 2011

Experimental Results









Conclusions

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- An Dual-Step-Mixing ILFD using a Even-Harmonic Direct Injection Technique is proposed for an enhanced locking range of divide-by-6 and divide-by-4 operations
- It achieves the widest locking range reported for divide-by-6 operation and comparable performance with the state-of-the-art divide-by-4 ILFDs
- This work is suitable to be integrated in push-push or sub-harmonic injection-locked 60GHz PLLs

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Thank you for your interest

Acknowledgement

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High Speed Frequency Dividers

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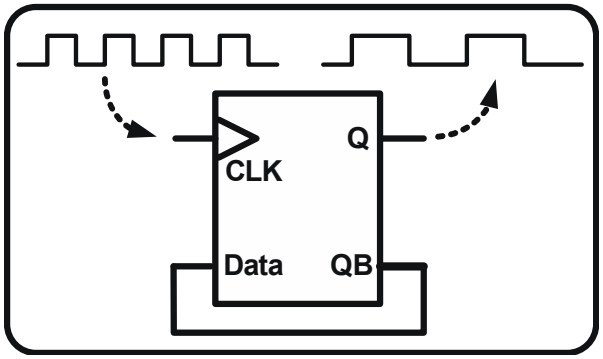
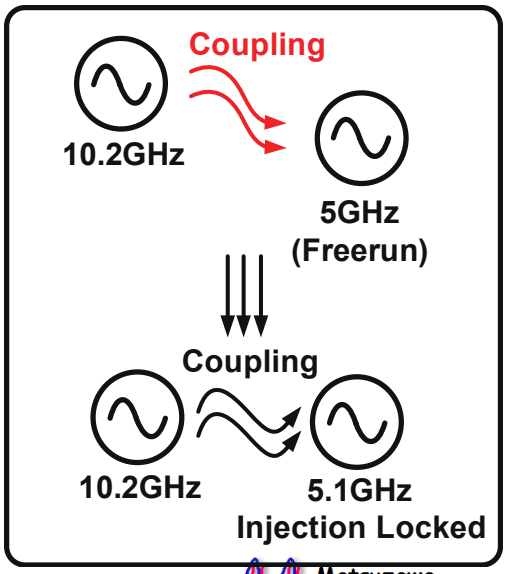
- High speed frequency dividers and VCO are the most power hungry parts of modern high frequency PLLs.

- Static Frequency Dividers:
  - Wide locking range
  - Consume considerable power
  - Conventionally only divides by 2
- Injection Locked Frequency Dividers (ILFDs)
  - Limited locking range
  - Low power consumption
  - Can divide by higher than 2





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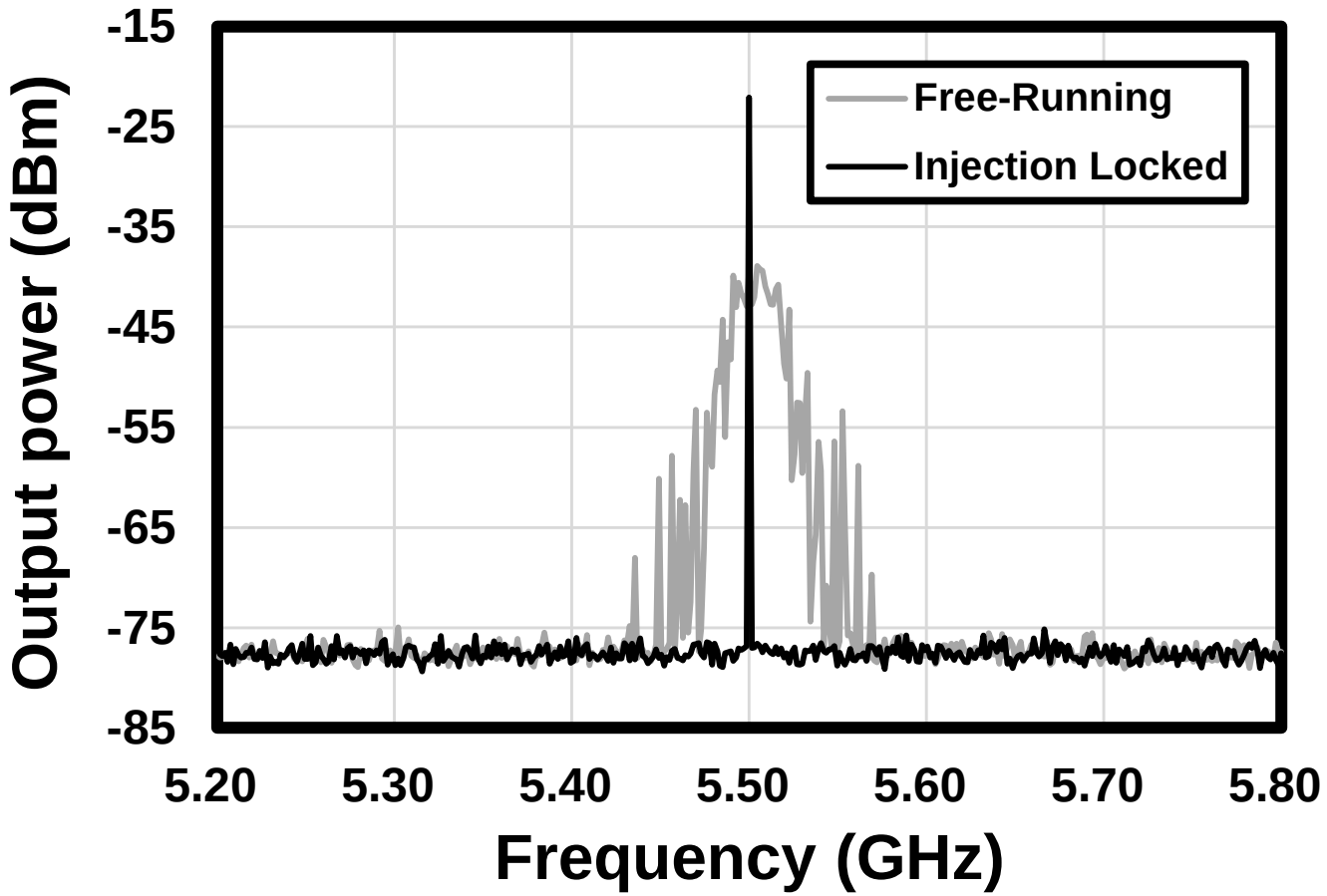
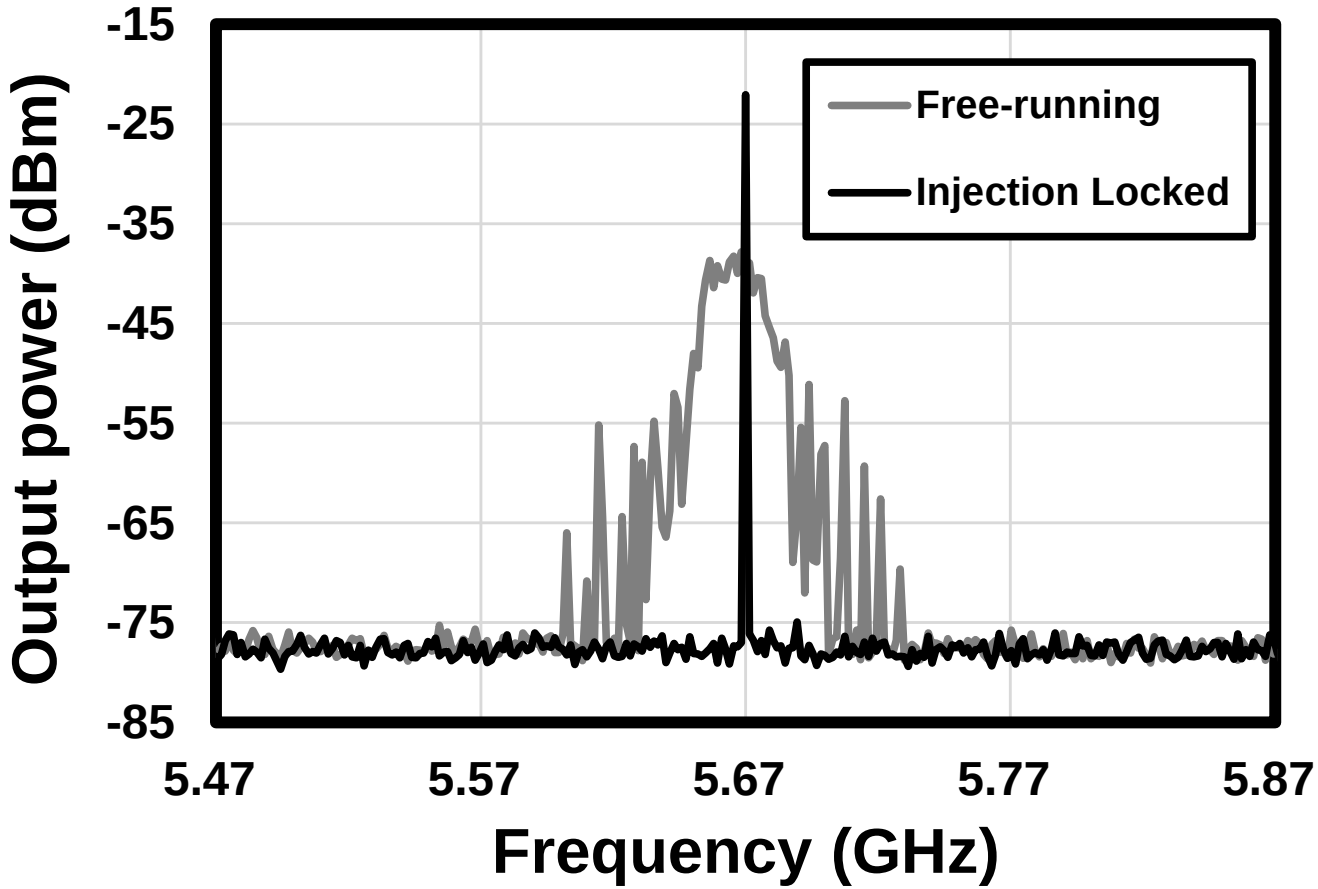
Locked Spectrum for Divide-by-4 mode



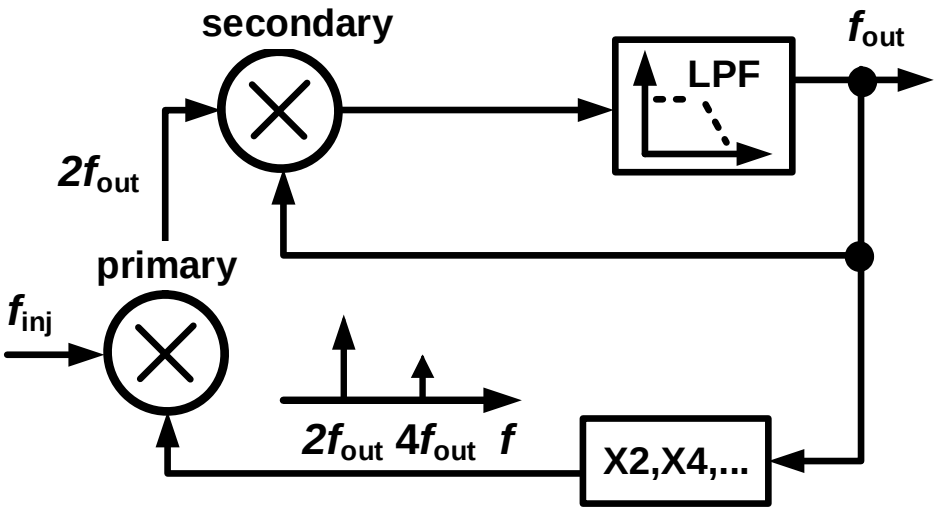
- **Injection frequency of 22GHz is applied**

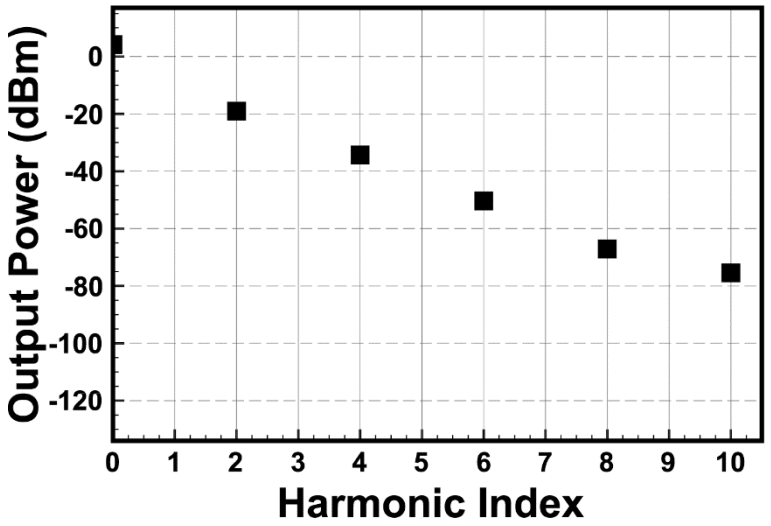
Locked Spectrum for Divide-by-6 mode



- **Injection frequency of 34GHz is applied**

Dual-Step Mixing using Direct Injection





- **Dual-step mixing mechanism for divide-by-4 and divide-by-6 operation**