学生 30

ミリ波64QAM通信を実現する60GHz帯局部発振器

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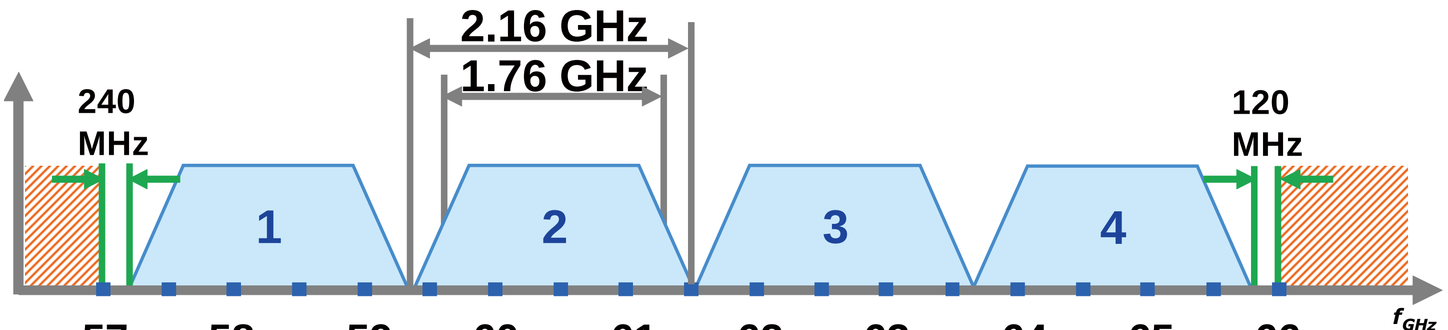
60GHz帯

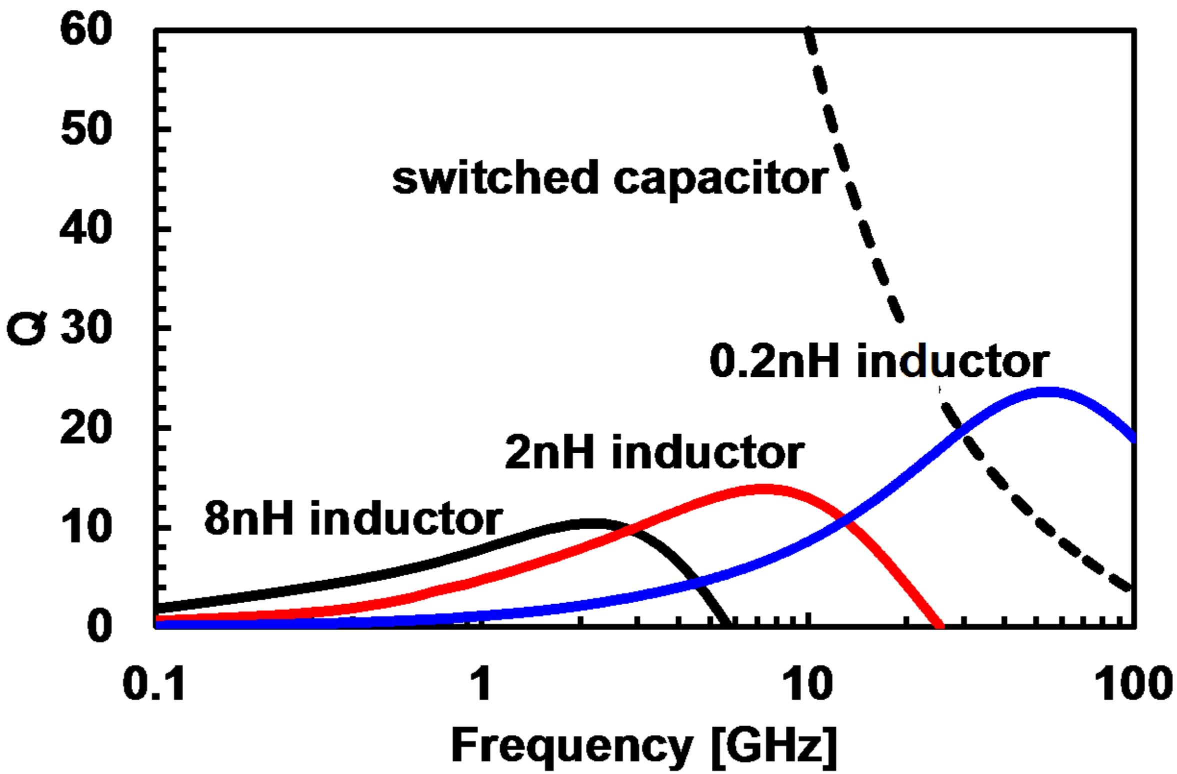
- QPSK ➔ 3.52Gbps/ch
- 16QAM ➔ 7.04Gbps/ch
- 64QAM ➔ 10.56Gbps/ch (not reported yet)

- 局部発振器の要求性能
  広帯域: 58.32-64.80 GHz
  低位相雑音: -96dBc/Hz@1MHz for 64QAM



from IEEE802.11ad/WiGig

60GHz帯発振器の課題

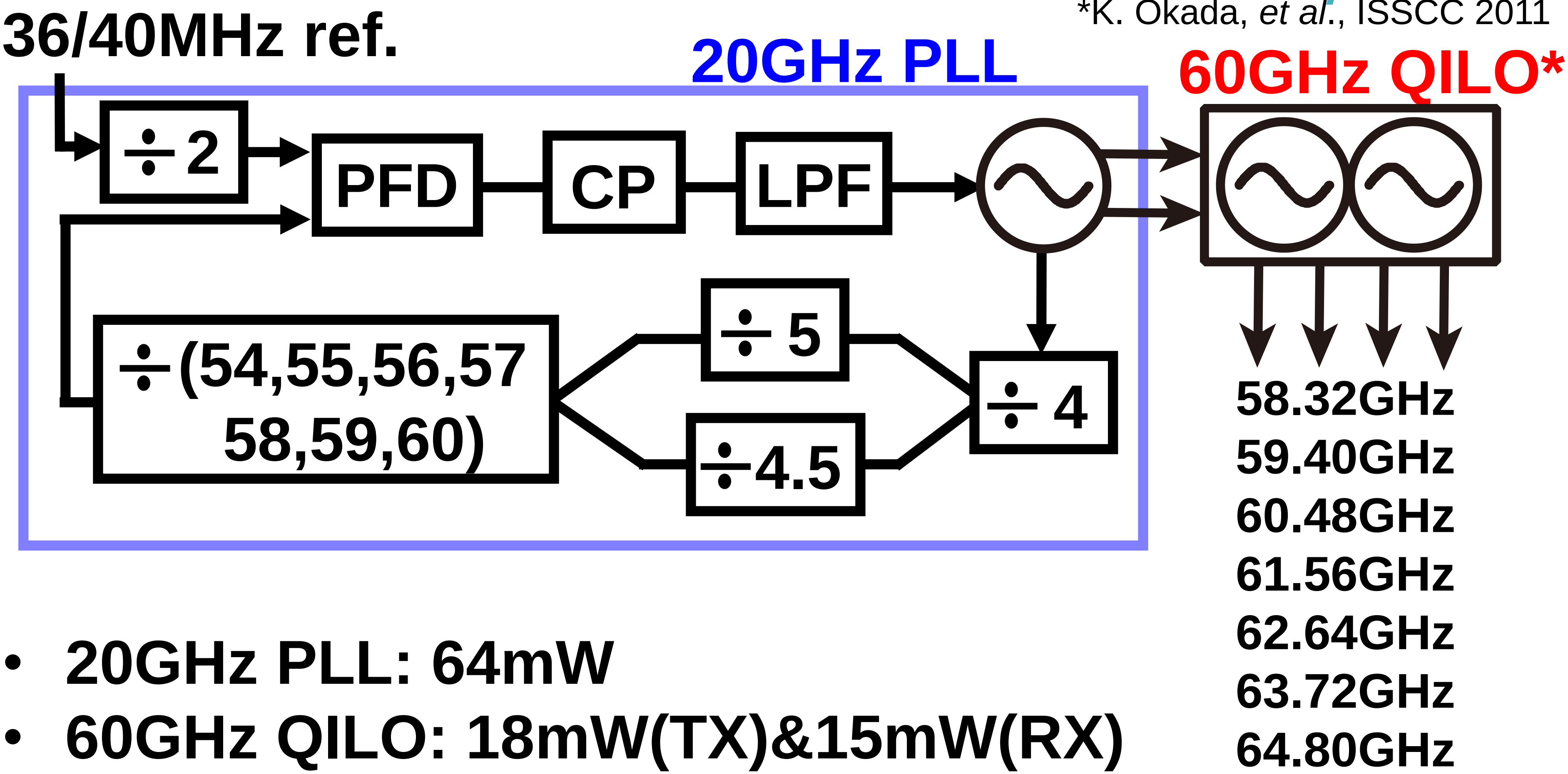


☹ 60GHz帯では表皮効果によりQ値が劣化
（Qc < 10 @ 60GHz）

低位相雑音と広帯域の両立が困難

60GHz帯局部発振器

*K. Okada, *et al*., ISSCC 2011



- 20GHz PLL: 64mW
- 60GHz QILO: 18mW(TX)&15mW(RX)
- QILO frequency range: 58-66GHz
- Phase noise improvement by injection locking*

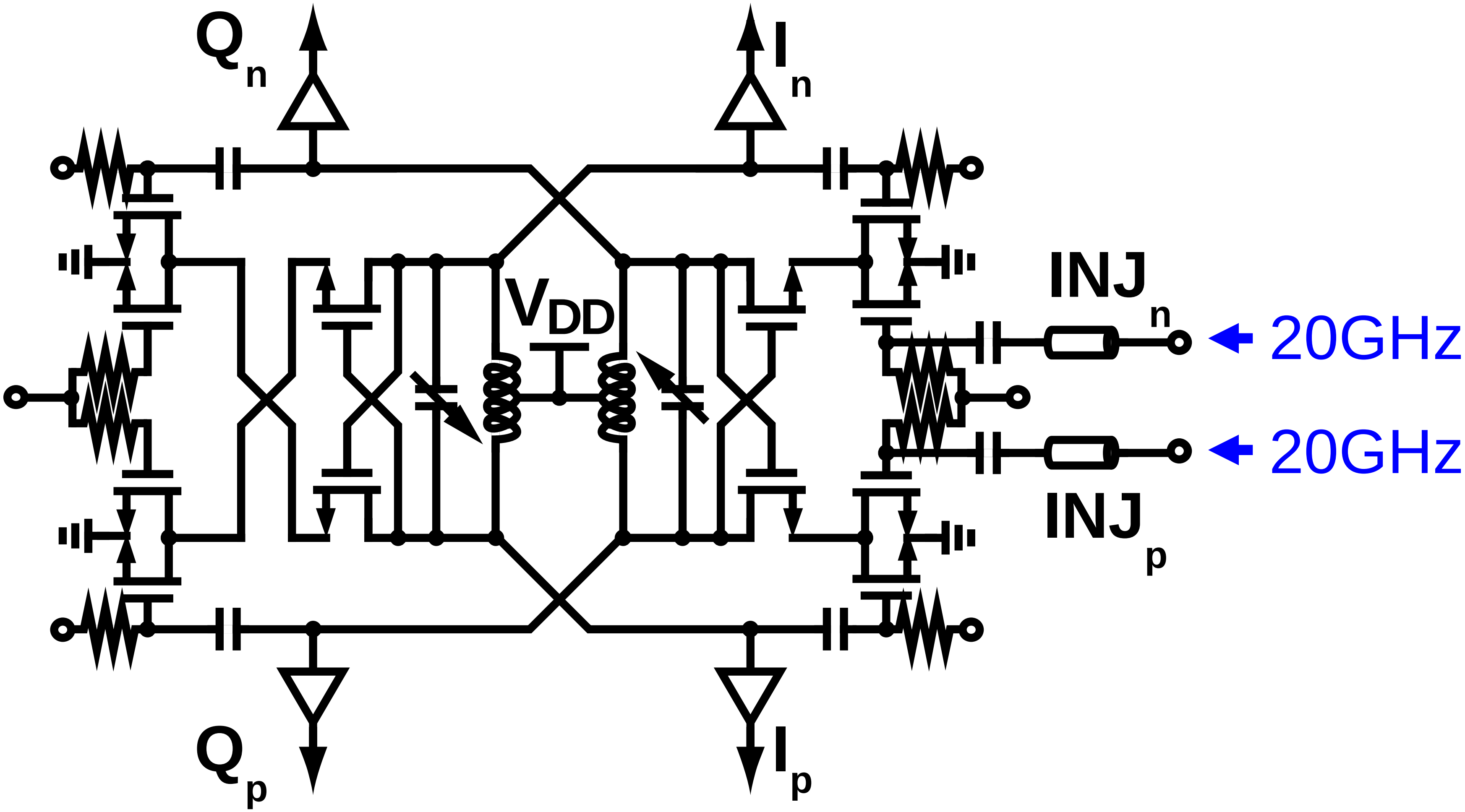
60GHz帯局部発振器の性能比較

Ref.	REF Freq. (MHz)	Frequency (GHz)	Phase Noise @1MHz	Features	Power (mW)
[1]	100	57.0-66.0	-75dBc/Hz	Direct 60GHz QPLL	78
[2]	203.2	59.6-64.0	-92dBc/Hz	30GHz PLL + hybrid	76
[3]	100	56.4-63.4	-90dBc/Hz	60GHz AD-PLL	48
This[4]	36	58.1-65.0	-96dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	72
This[5]	36/40	58-66	-97dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	79
This	36/40	58.3-65.4	-95dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	33

世界初:60GHz帯全チャネル64QAM通信を実現[5]

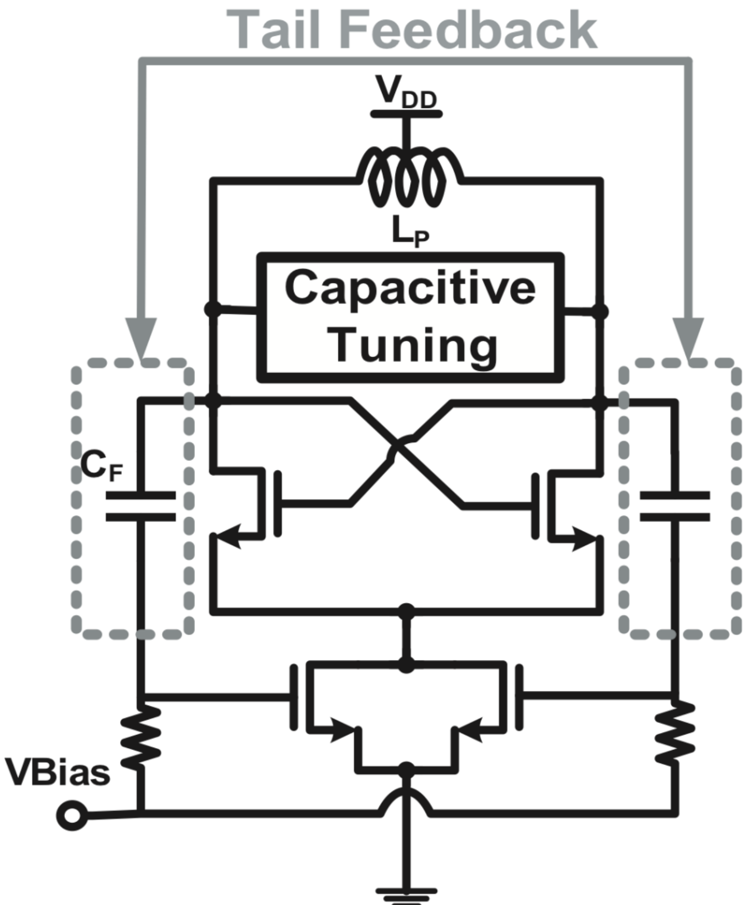
[1] K. Scheir, *et al*., ISSCC 2009 [2] C. Marcu, *et al*., JSSC 2009 [3] W. Wu, *et al*., ISSCC 2013
[4] W. Deng, *et al*., JSSC 2013 [5] K. Okada, *et al*., ISSCC 2014

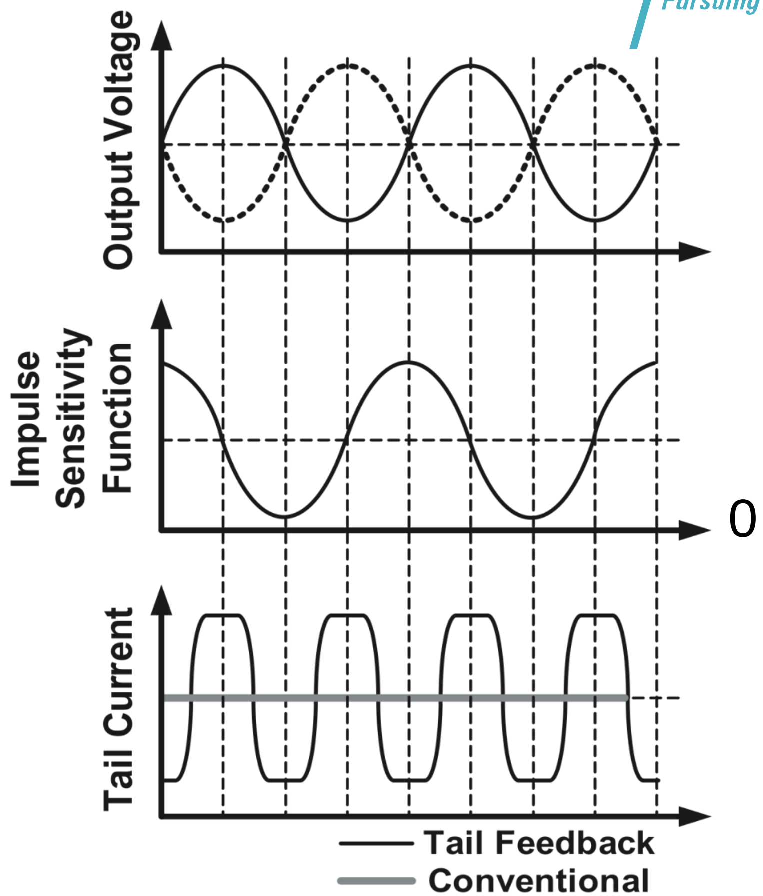
60GHz QILO



*W. Chan, *et al*., ISSCC 2008 **A. Musa, *et al*., JSSC 2011 ***K. Okada, *et al*., ISSCC 2011, 2012

20GHz VCO



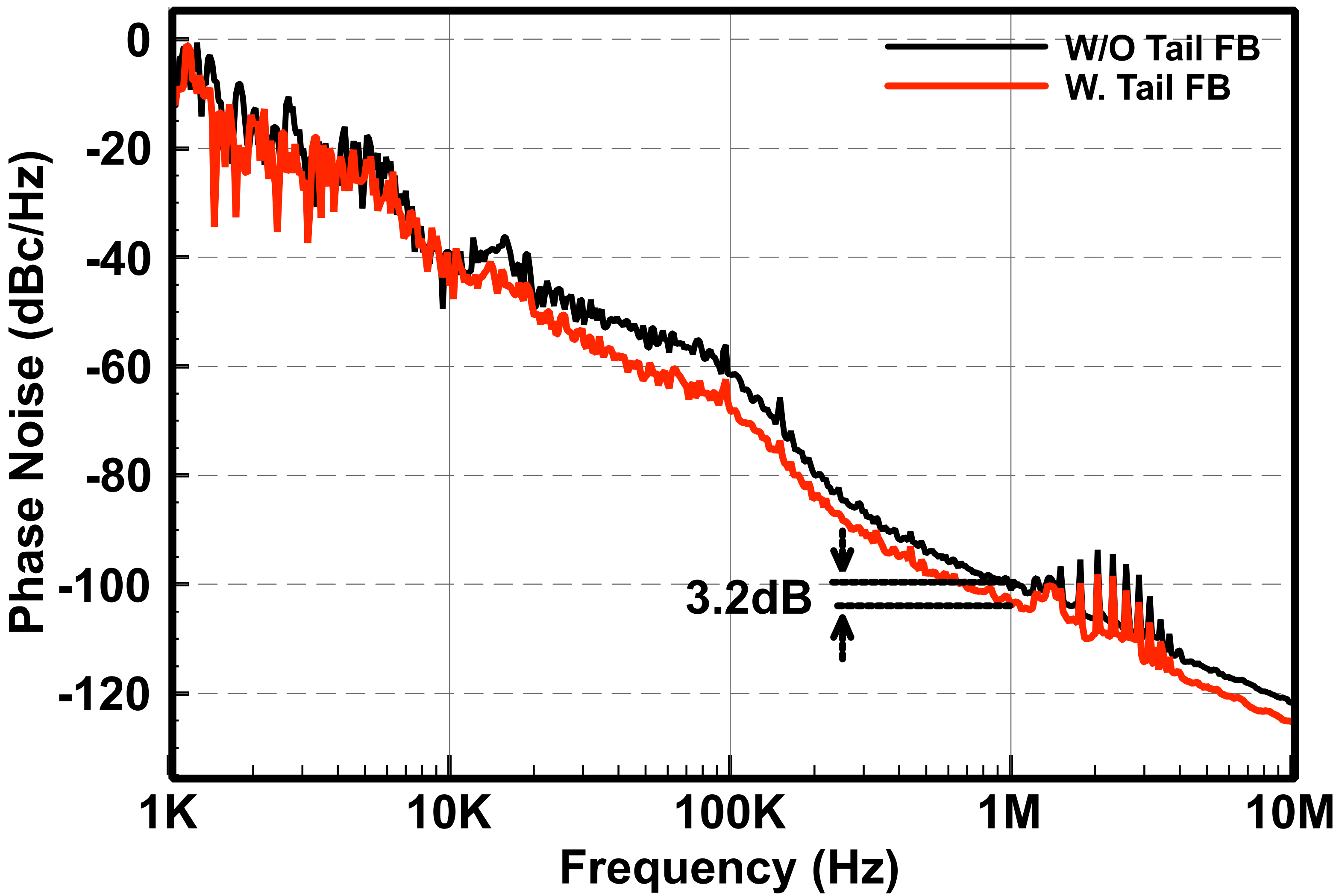


☺ 雑音感度の低いポイントで駆動させる

位相雑音-107dBc/Hz@1MHz を達成

*K. Okada, *et al*., JSSC 2011

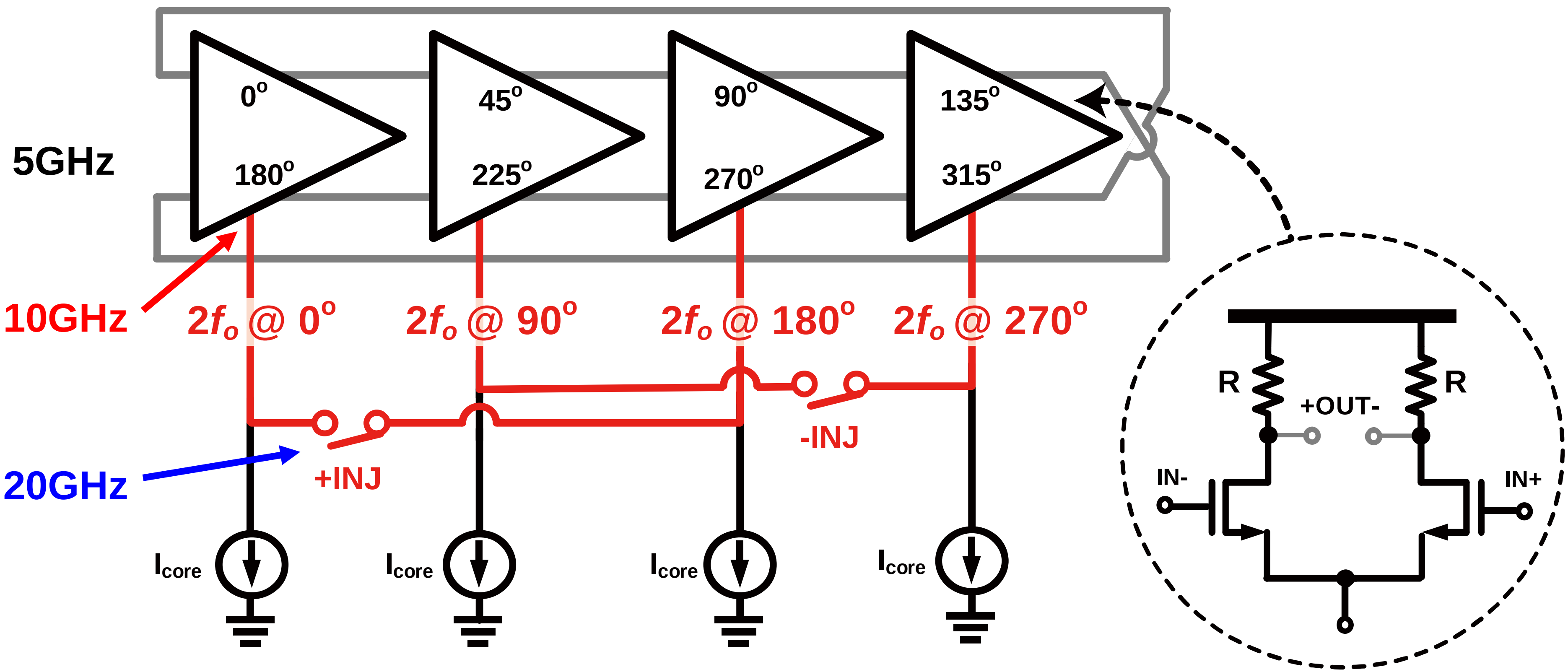
位相雑音の比較



*A. Musa, *et al*., IEICE Trans. Electron. 2013

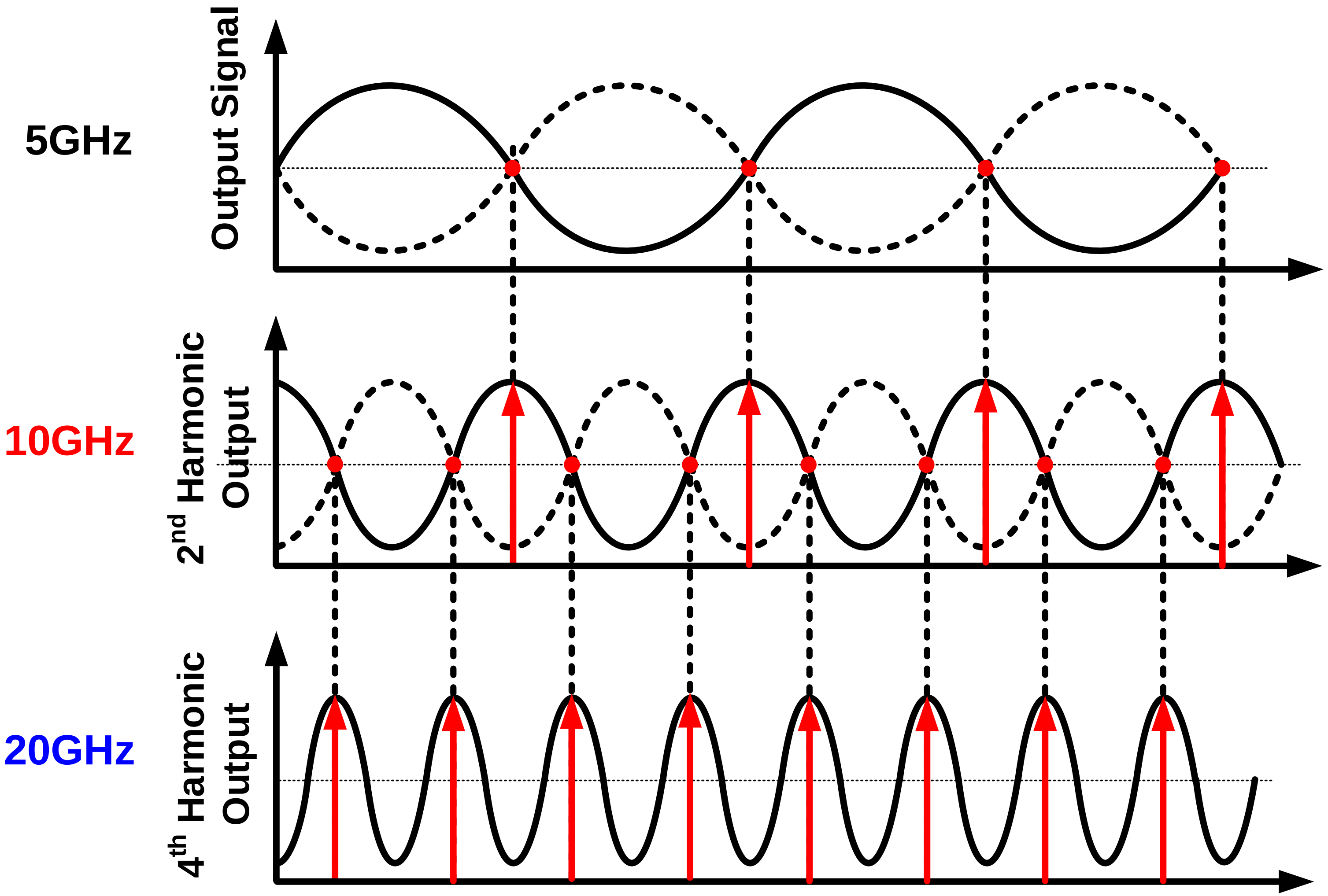
20GHz-to-5GHz ILFD (/4)

Progressive-mixing ILFD*,**



*A. Musa, *et al*., A-SSCC 2011 **T. Siriburanon, *et al*., ESSCIRC 2013

4分周時の動作



Locked State of Divide-by-4 operation

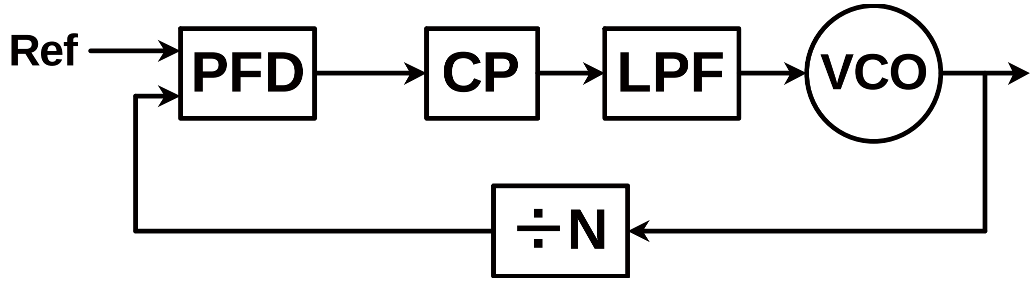
4分周器の性能比較

	Features	Locking Range (GHz)	Power (mW)	Area (mm^2)
[1]	Direct mixing	22.6-28 (21%)	8.3	0.140
[2]	Direct mixing	31.0-41.0 (27%)	3.3	0.002
[3]	LC Direct mixing	58.5-72.9 (22%)	2.2	0.032
[4]	CML + LC ILFD	13.5-30.5 (77%)	7.3	0.33
This [5]	Progressive mixing	13.4-21.3 (31%)	3.9	0.003
This [6]	Progressive mixing	15.2-20.4 (24%)	3.1	0.002

[1] A-SSCC 2007 [2] ISSCC 2006 [3] CICC 2012 [4] T-MTT 2011
[5] A. Musa, *et al*., A-SSCC 2011 [6] T. Siriburanon, *et al*., ESSCIRC 2013

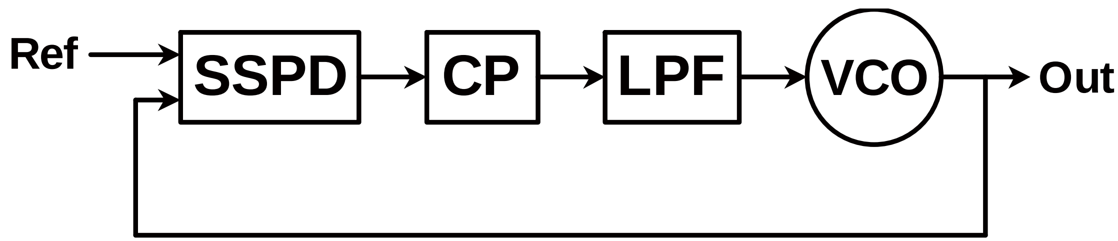
サブサンプリングPLL

- 従来回路（チャージポンプPLL）



PD：Phase Frequency Detector
CP：Charge Pump
LPF：Low Pass Filter

- 提案回路（サブサンプリングPLL）

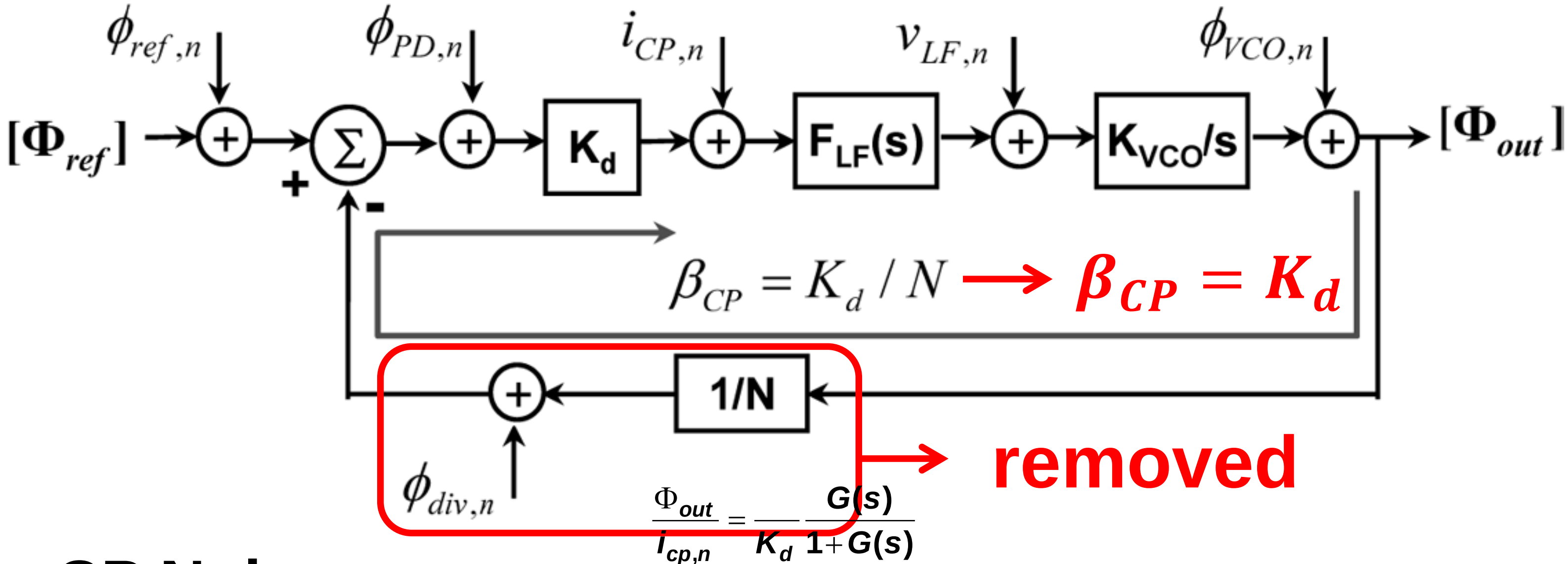


SSPD：Sub-Sampling Phase Detector

☺ 分周器のノイズがなくなる
☺ 分周器によるループ帯域内雑音の増幅がなくなる
☹ フリーラン周波数が所望の周波数と離れているとSSPDが位相差を正しく検出できない
☹ ロック動作には別のfrequency locked loopが必要

*X.Gao, *et al*., JSSC 2009

伝達関数



For CP Noise;

$$\frac{\Phi_{out}}{i_{CP,n}} = \frac{N}{K_d} \frac{G(s)}{1+G(s)} \longrightarrow \frac{\Phi_{out}}{i_{CP,n}} = \frac{1}{K_d} \frac{G(s)}{1+G(s)}$$

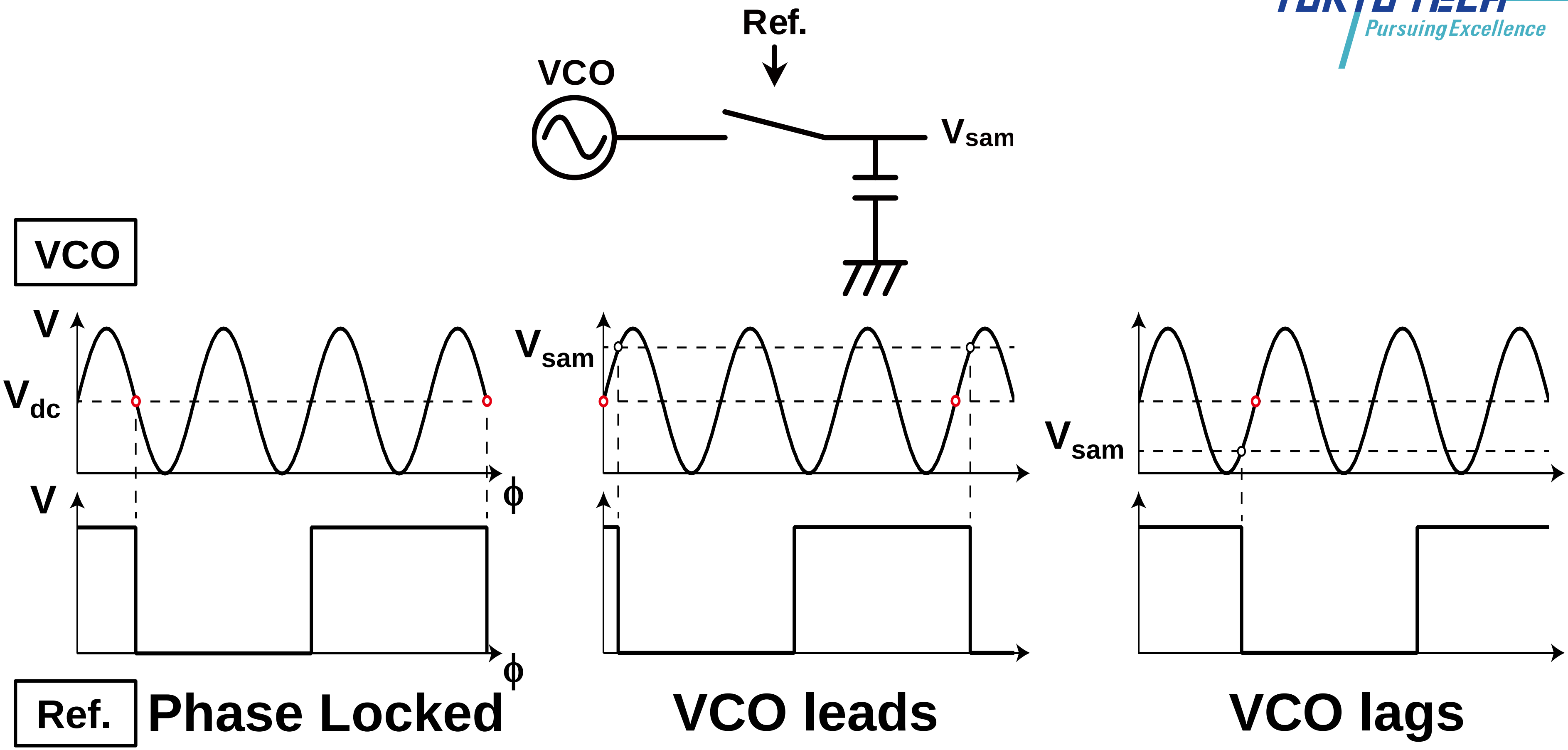
($G(s)$ is loop transfer function)

☺ ループ帯域内のノイズがN倍されない

→分周比が大きくなる高周波では特に有利

*X.Gao, *et al*., JSSC 2009

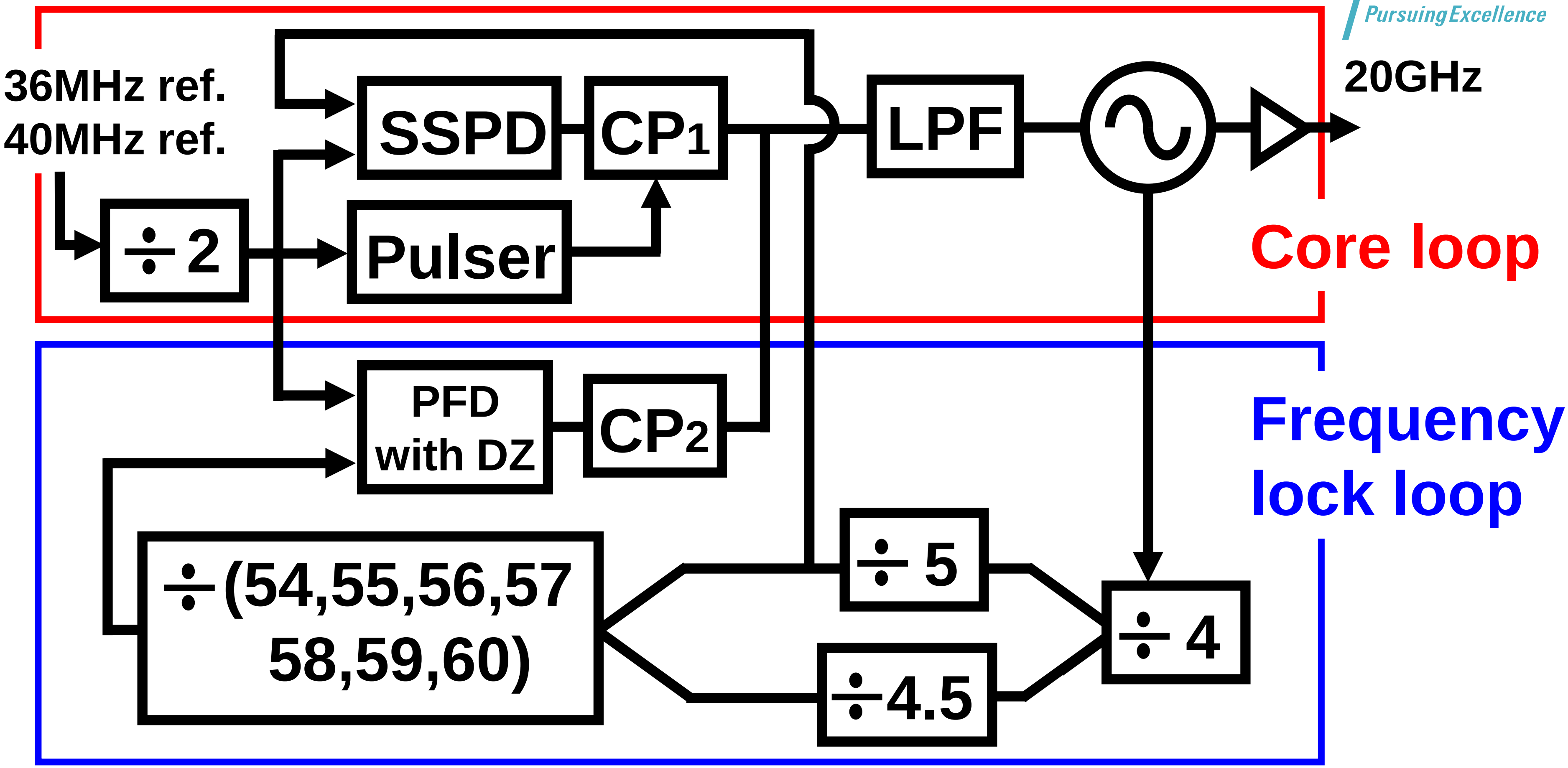
サブサンプリング位相比較器



- 参照信号に対してVCOの位相が
  - 進んでいると $V_{sam}>V_{dc}$
  - 遅れていると $V_{sam}<V_{dc}$

☺ 分周器が不要

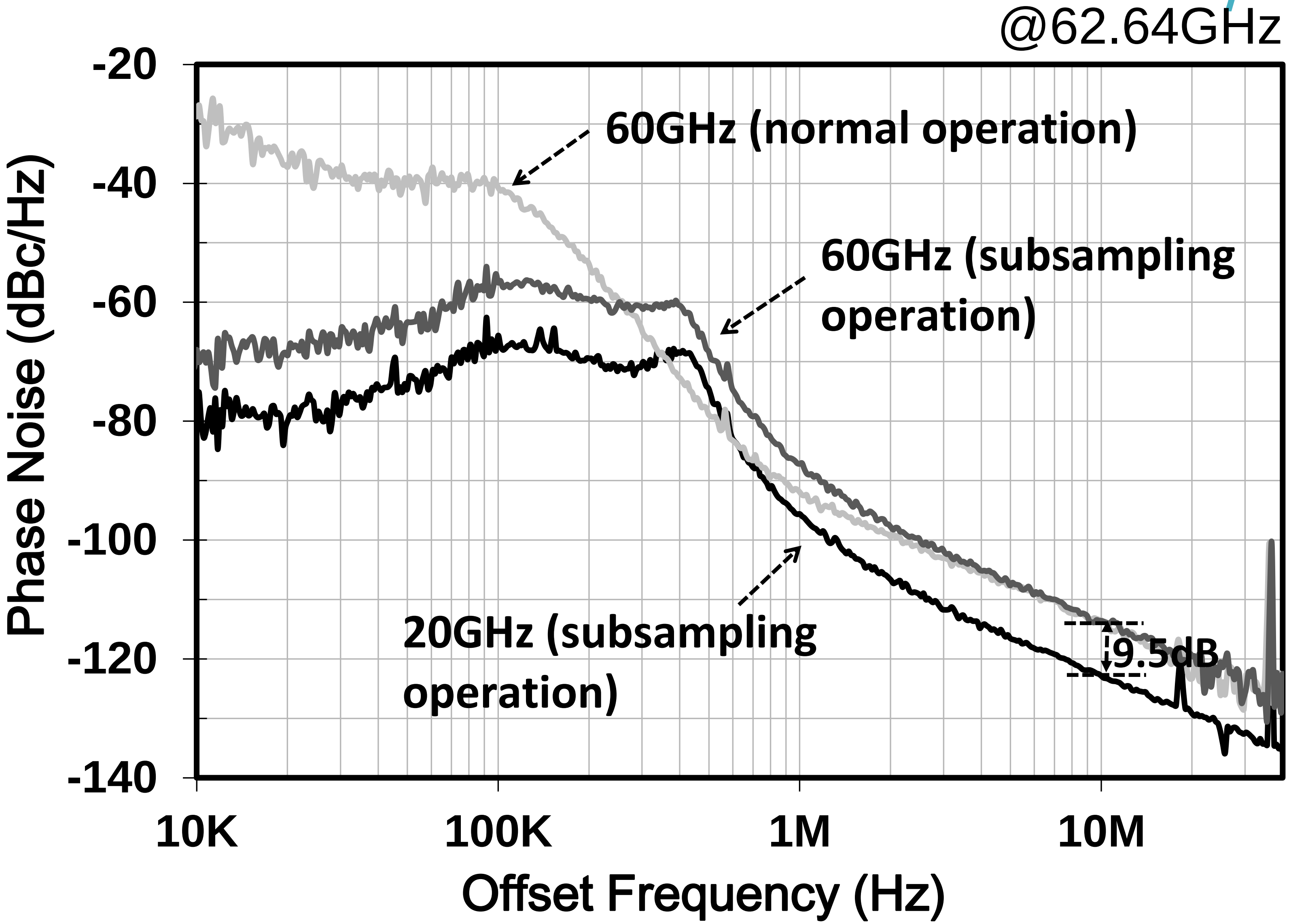
回路構成



- Frequency lock loopで周波数をロック
- ロック後はCore loopに切り替える

*V. Szortyka, *et al*., ISSCC 2014

位相雑音


@62.64GHz
-20
-40
-60
-80
-100
-120
-140
Phase Noise (dBc/Hz)
60GHz (normal operation)
60GHz (subsampling operation)
20GHz (subsampling operation)
9.5dB
10K
100K
1M
10M
Offset Frequency (Hz)

性能比較

Ref.	REF Freq. (MHz)	Frequency (GHz)	Integrated Jitter (ps)	Phase Noise @10kHz offset	Phase Noise @10MHz offset	Features	Power (mW)
[1]	100	57.0-66.0	1.5	-66 dBc/Hz	-108 dBc/Hz	Direct 60GHz QPLL	78
[2]	203.2	59.6-64.0	2.3	-65 dBc/Hz	-112 dBc/Hz	30GHz PLL + Coupler	76
[3]	100	56.0-62.0	0.94	-71 dBc/Hz	-109 dBc/Hz	60GHz AD-PLL	48
This (normal)	36/40	58.3-65.4	12.0	-40 dBc/Hz	-115 dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	32.8
This (SS)	36	58.3-65.4	2.1	-69 dBc/Hz	-115 dBc/Hz	Sub-harmonic Injection 20GHz SS-PLL + 60GHz QILO	34.2

[1] K. Scheir, *et al*., ISSCC 2009 [2] C. Marcu, *et al*., JSSC 2009 [3] W. Wu, et al., ISSCC 2013

結論

- 60GHz帯局部発振器を開発
  位相雑音-97dBc/Hz@1MHzを達成
- 世界初:60GHz帯における
  全チャネル64QAM通信を実現
  - 20GHz PLL + 60GHz QILO
  - 20GHz Tail Capacitive-Feedback VCO
  - 20GHz-to-5GHz Progressive-mixing ILFD
- PLLにサブサンプリングを用いることにより
  ループ帯域内位相雑音を改善
  -40dBc/Hz→-69dBc/Hz@10kHz