A 5GHz, 1mW CMOS Voltage–Controlled Differential Injection–Locked Frequency Divider

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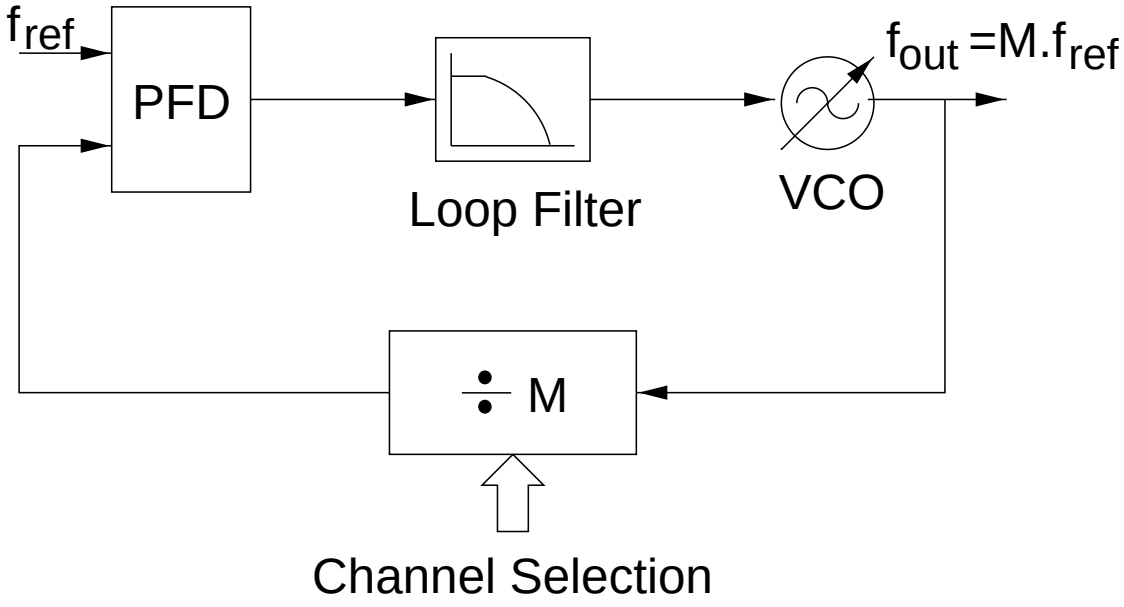
OUTLINE

- motivation
- injection–locked frequency dividers (ILFDs)
  - mathematical model
  - circuit implementation
  - design issues
    - optimal inductor design
- measurement results
- summary
- conclusion

MOTIVATION

- wireless systems:
  - are narrowband
  - require frequency synthesizers
  - require low power operation
- PLL–based frequency synthesizer require frequency dividers
- conventional dividers:
  - wideband
  - power hungry



IDEA

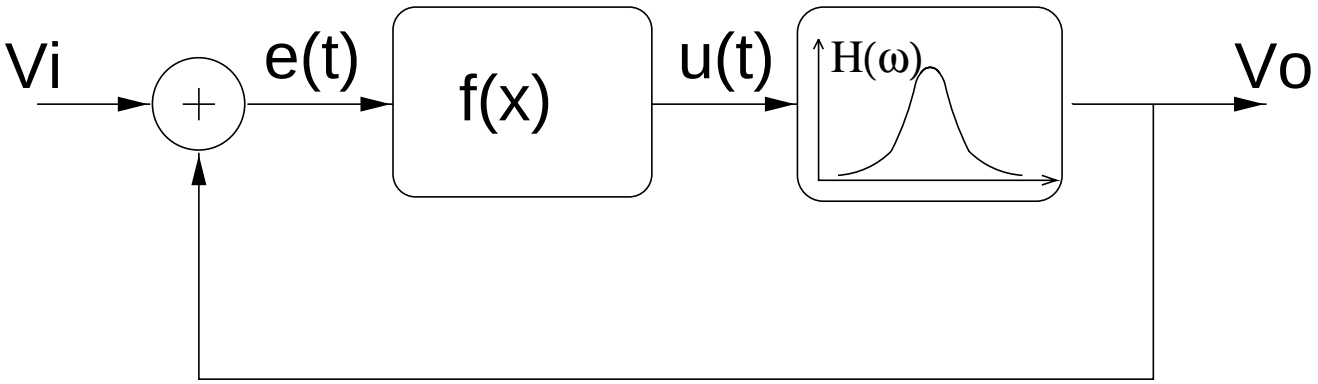
- design a low–power and narrowband frequency divider

use resonators to trade off bandwidth for power

INJECTION–LOCKED OSCILLATORS

- by impressing an oscillator with an external (incident) signal, frequency locking can be achieved
  - first-harmonic injection locked oscillators ($f_i = f_o$)
  - subharmonic injection locked oscillators ($f_i = \frac{1}{N} f_o$)
  - superharmonic injection locked oscillators ($f_i = N \times f_o$) injection–locked frequency dividers (ILFDs)

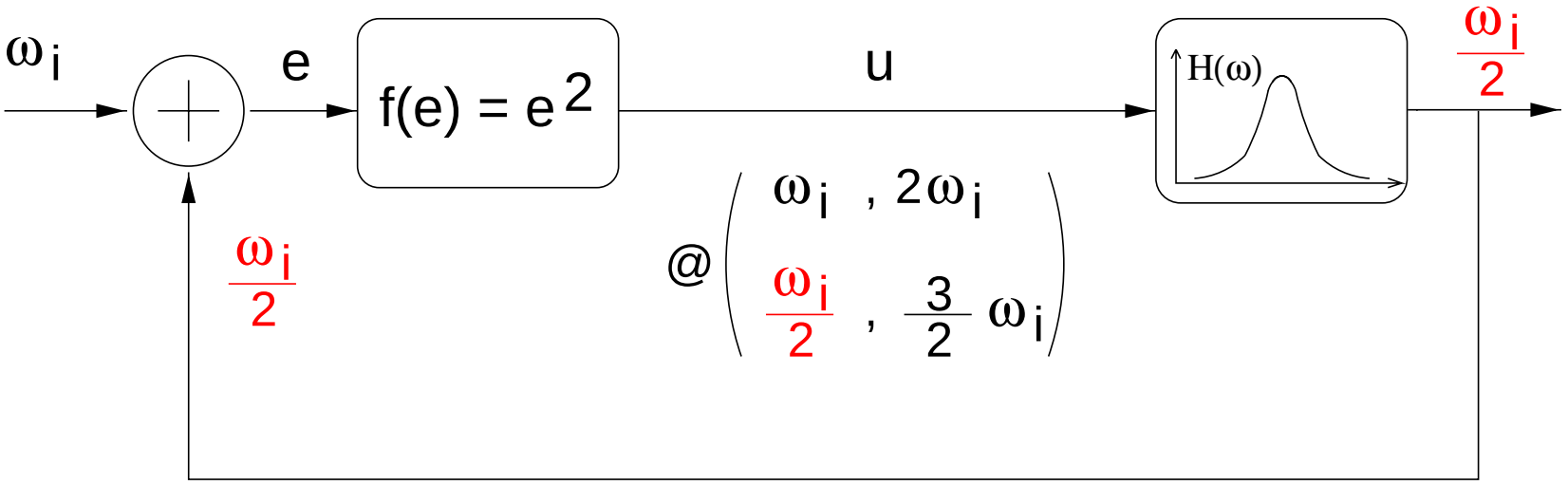
ILFD MODEL



$$
\begin{aligned}
v_o(t) &= V_o cos(\omega_o t) \\
v_i(t) &= V_i cos(\omega_i t + \phi) \\
u(t) &= f[e(t)] = f[v_o(t) + v_i(t)] \\
H(\omega) &= \frac{H_0}{1 + j2Q\frac{\omega - \omega_r}{\omega_r}}
\end{aligned}
$$

- oscillation condition should be satisfied in the presence of the incident signal.

SIMPLIFIED PICTURE



$$e = cos(\omega_i t) + cos(\frac{\omega_i}{2} t)$$

$$u = [cos(\omega_i t) + cos(\frac{\omega_i}{2} t)]^2$$

$$u = 1 + \frac{1}{2} cos(2\omega_i t) + \frac{1}{2} cos(\omega_i t) + cos(\frac{3\omega_i}{2} t) + cos(\frac{\omega_i}{2} t)$$

Special case (divide–by–two)

$$f(e) = a_0 + a_1 e + a_2 e^2 + a_3 e^3$$

- phase condition:

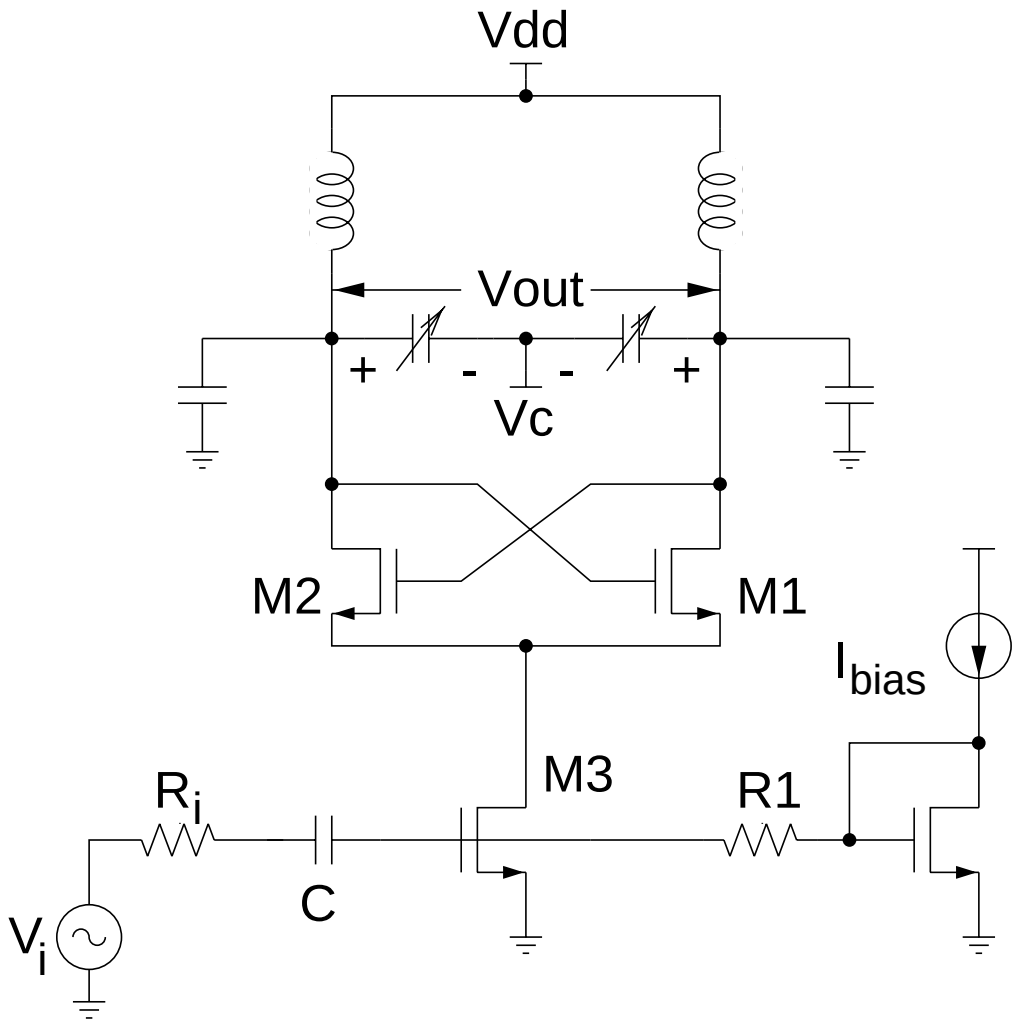
$$|\frac{\Delta\omega}{\omega_r}| < |\frac{H_0 a_2 V_i}{2Q}| \qquad , \qquad \frac{H_0}{Q} = \frac{LQ\omega_r}{Q} = L\omega_r$$

- gain condition:

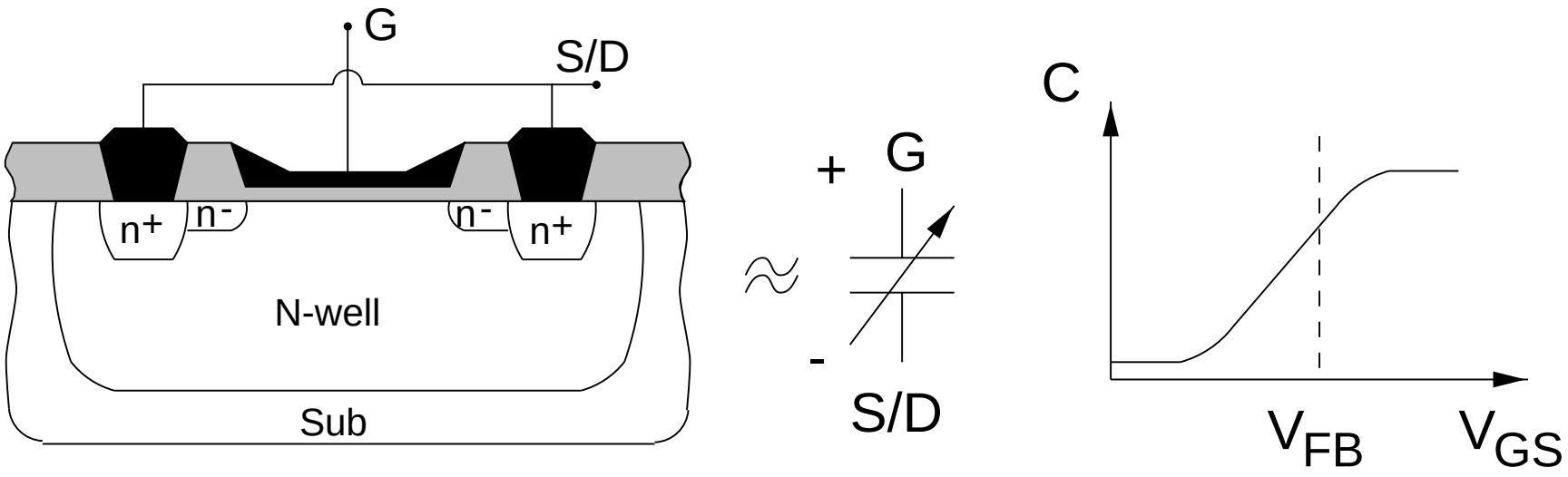
$$H_0(a_1 + \frac{3}{2}a_3 V_i^2 + a_2 V_i cos(\phi)) < 1$$

VOLTAGE–CONTROLLED DIFFERENTIAL ILFD

- 0.24μm CMOS
- Vdd=1.5V
- $\mathrm{I_{bias}}$=300μA
- f_o=2.25GHz
- f_i=4.5GHz



VARACTOR

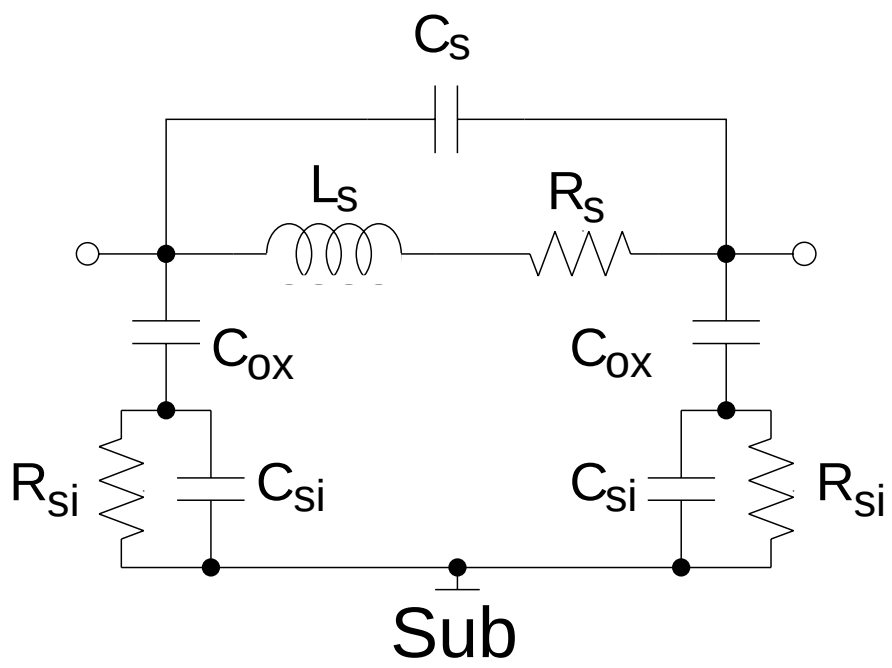


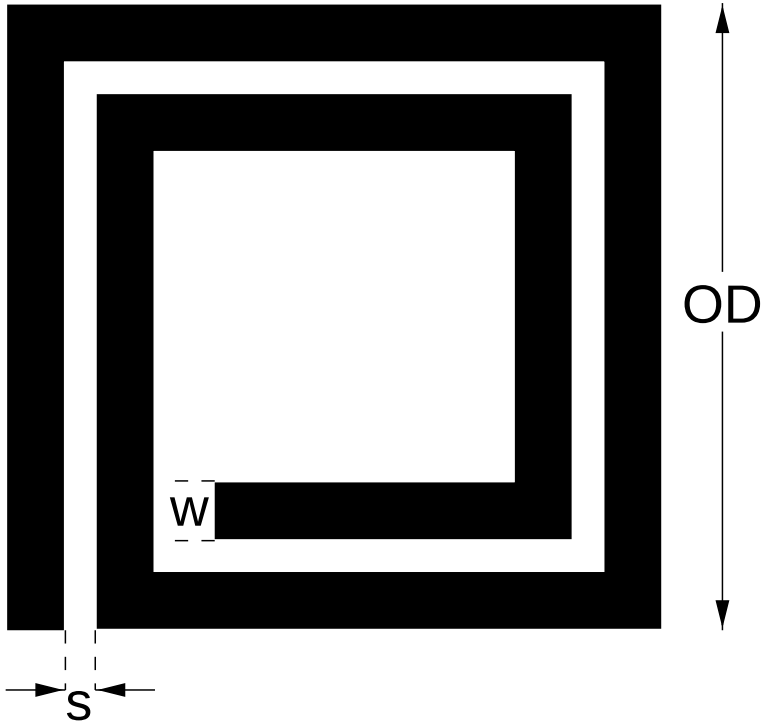
- accumulation mode MOS capacitor
  - large quality factor ($>$ 60 @ 2.5GHz)
  - flat–band voltage $\approx$ zero volt

INDUCTOR DESIGN

- maximum locking range $\Rightarrow$ maximize L
- minimum power consumption $\Rightarrow$ maximize LQ

INDUCTOR DESIGN





- design parameters:
  - w: metal width
  - s: metal spacing
  - OD: outer dimension
  - n: number of turns

INDUCTOR DESIGN

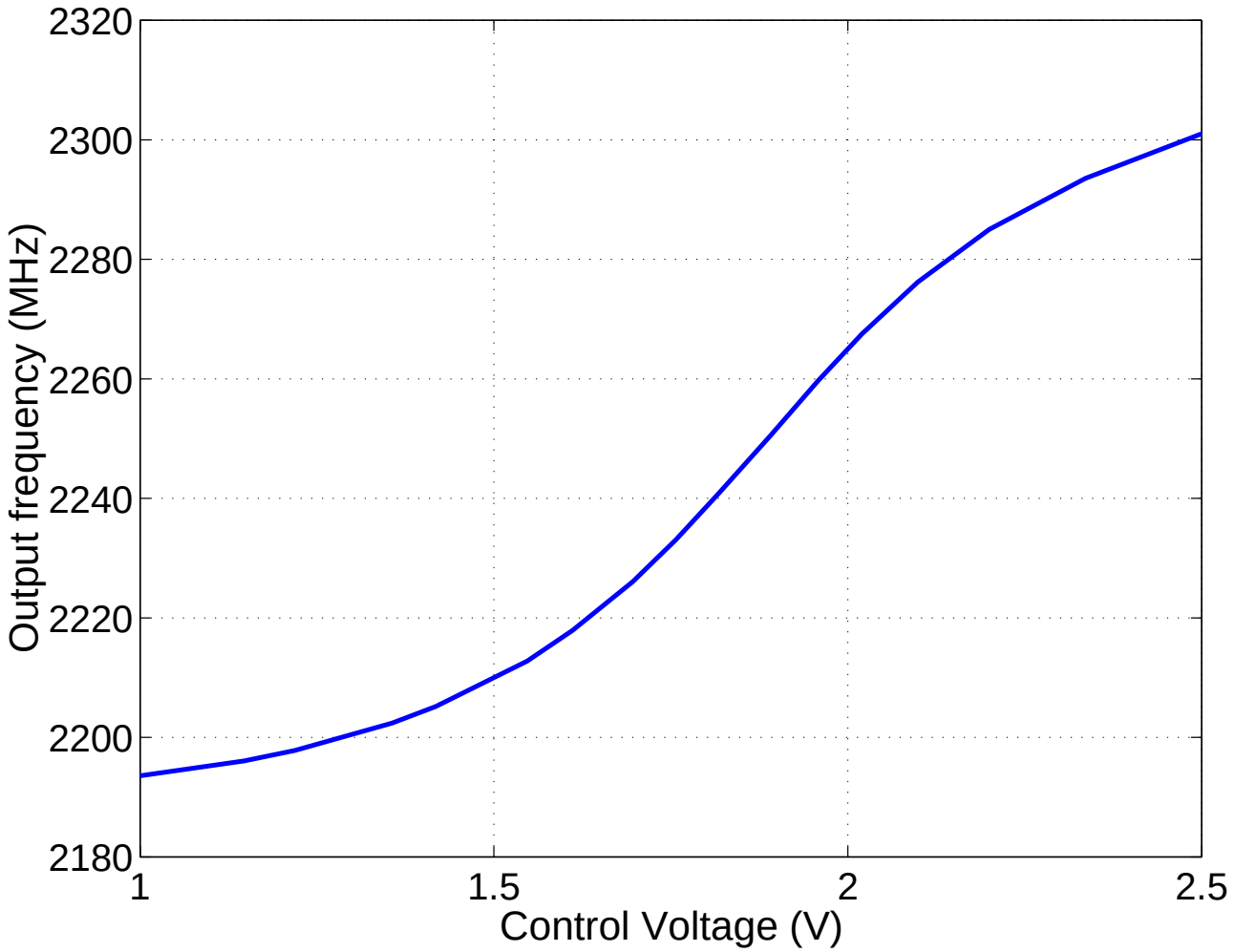
- in planar spiral inductors maximizing L does not maximize LQ

$$\Downarrow$$

maximize L for a given LQ

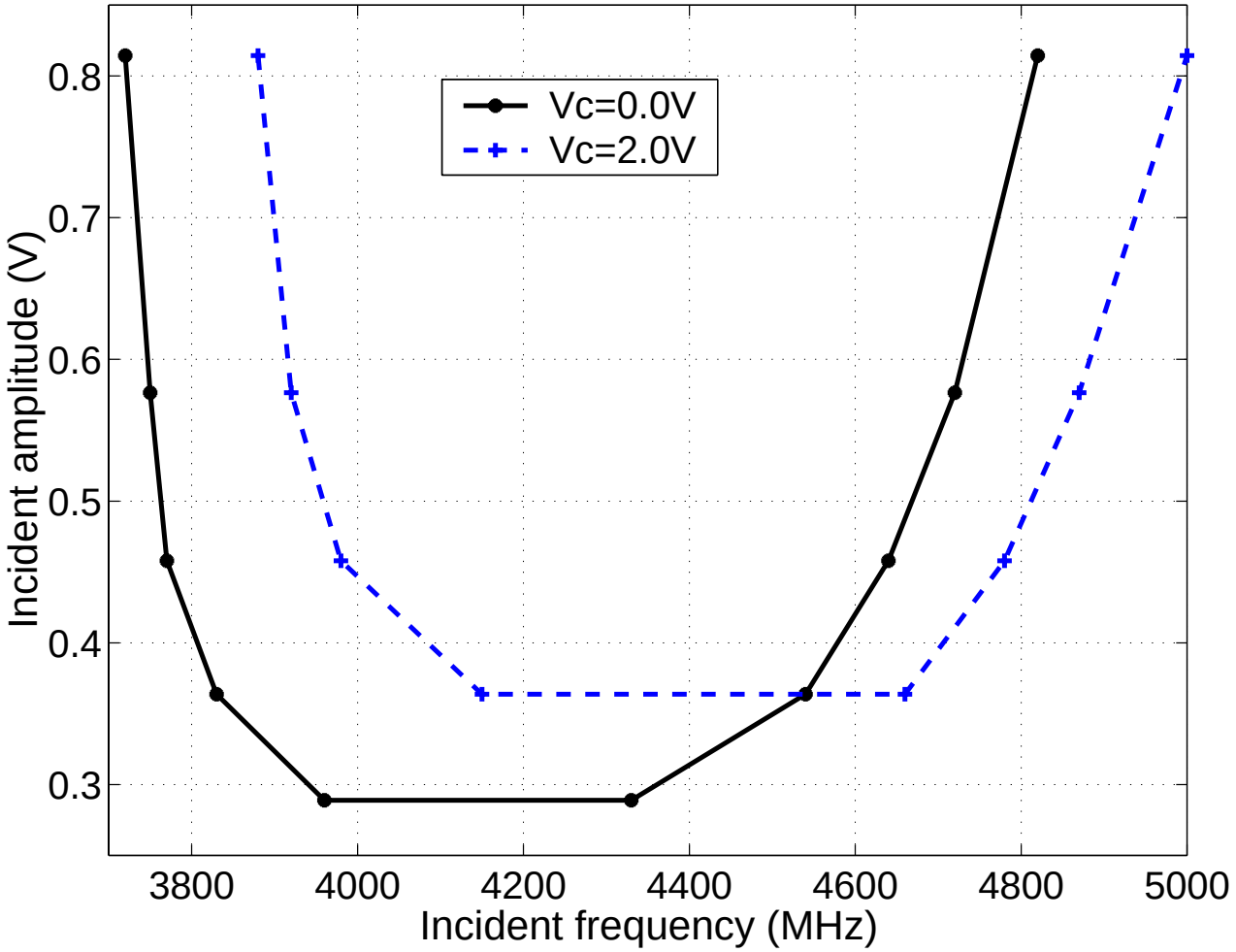
Measurement (free–running oscillation)

- 0.24μm CMOS
- Vdd=2.0V
- $\mathrm{I_{bias}}$=600μA
- Δf=110MHz
- $\frac{\Delta f}{f_o}$=5%
- ΔV_c=1.5V

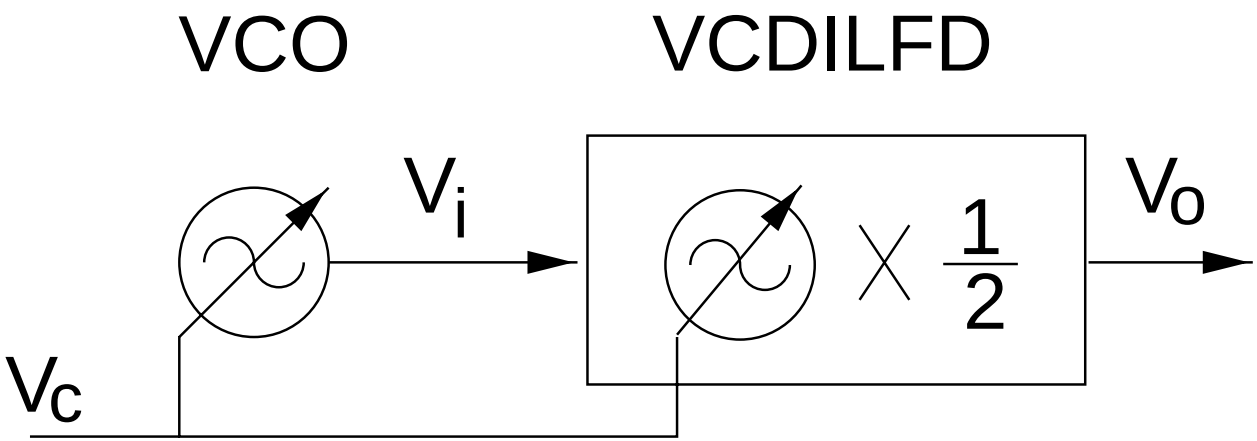


MEASUREMENTS (FREQUENCY RANGE)

- 0.24μm CMOS
- Vdd=1.5V
- I_{bias}=300μA



TRACKING ILFD

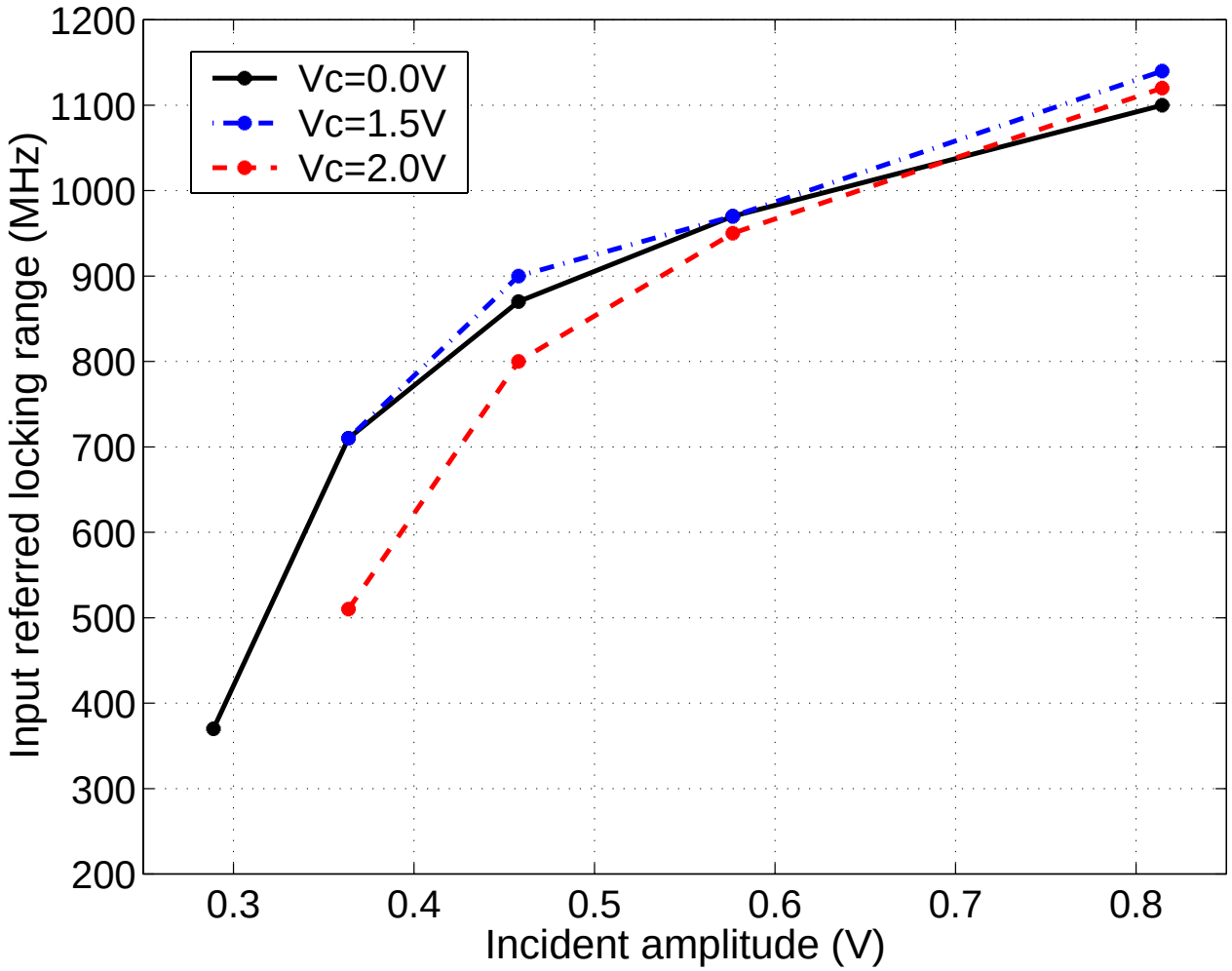


- locking range extension

Rategh *et al.*, symposium on VLSI circuits, June 1999, session 12.1

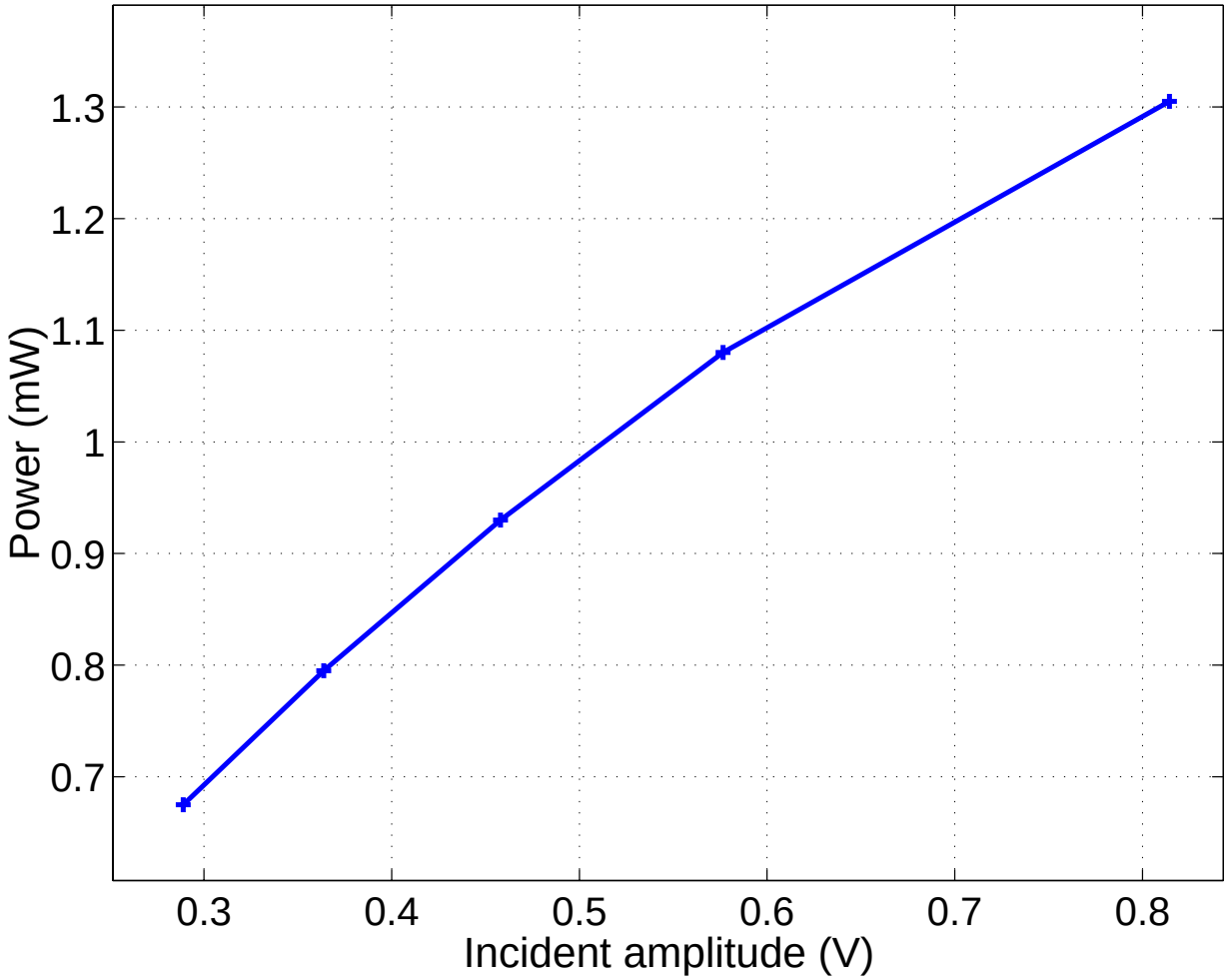
MEASUREMENTS (LOCKING RANGE)

- 0.24μm CMOS
- Vdd=1.5V
- f_o=2.2GHz
- f_i=4.4GHz
- Δf=900MHz
  $\approx$ 20% @ 0.5V

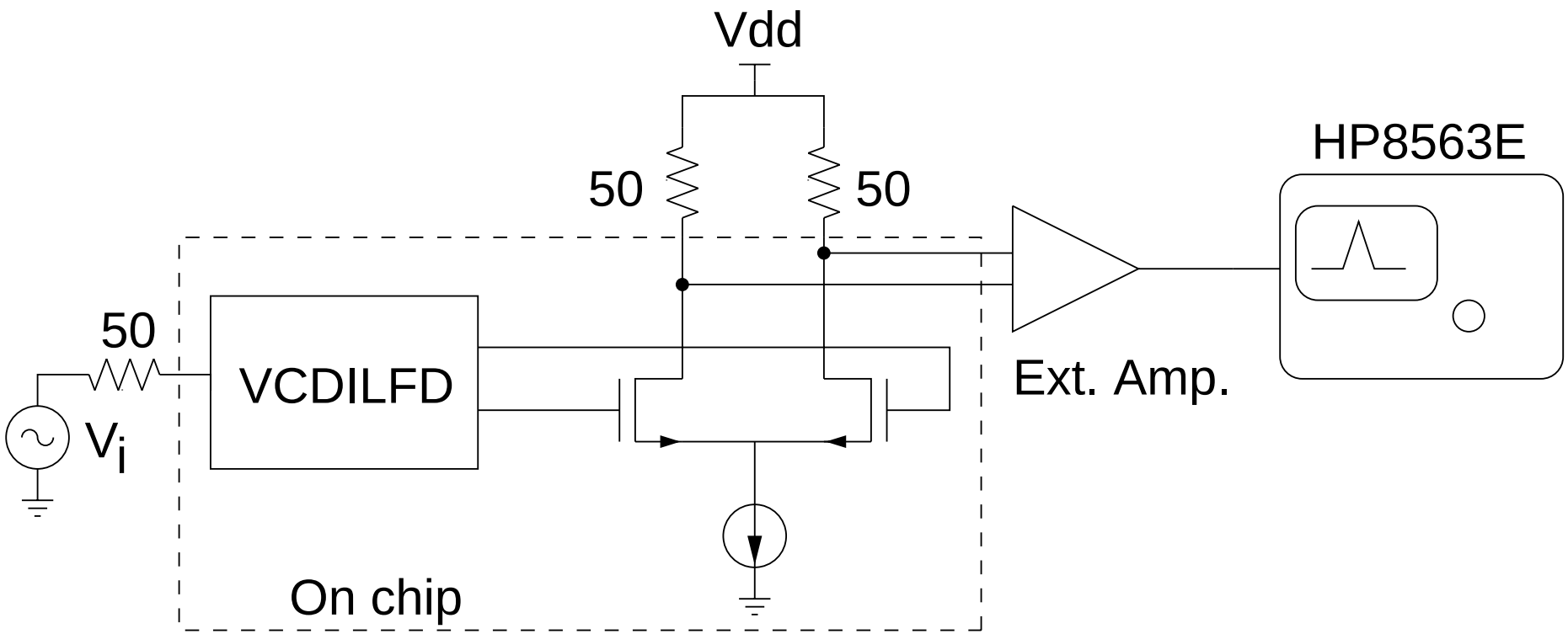


Measurements (power consumption)

- 0.24μm CMOS
- Vdd=1.5V
- f_o=2.2GHz
- f_i=4.4GHz
- P=1.0mW @ 0.5V



PHASE NOISE MEASUREMENT TEST SETUP



Measurements (phase noise)

- 0.24μm CMOS
- Vdd=1.5V
- f_o=2.2GHz
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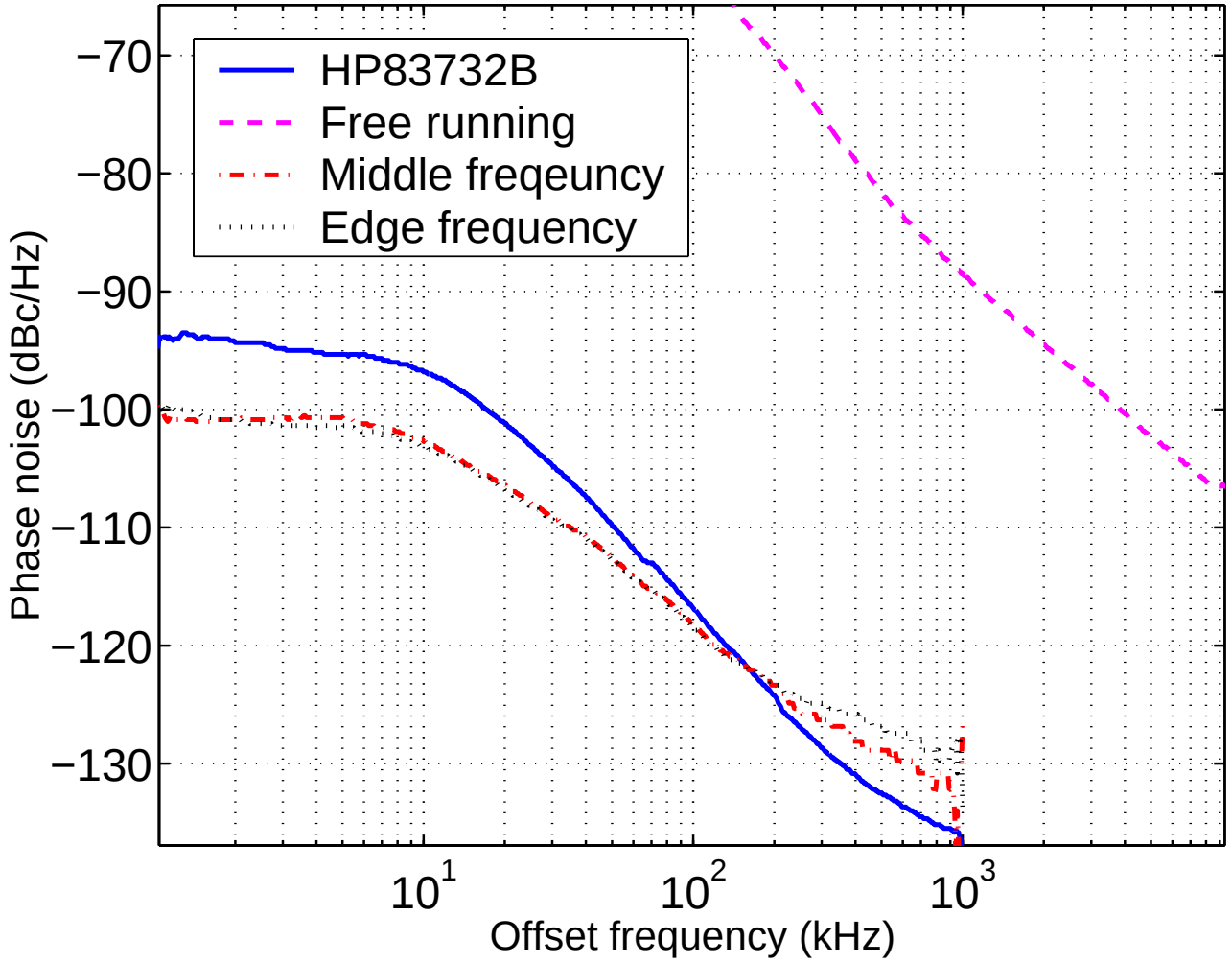
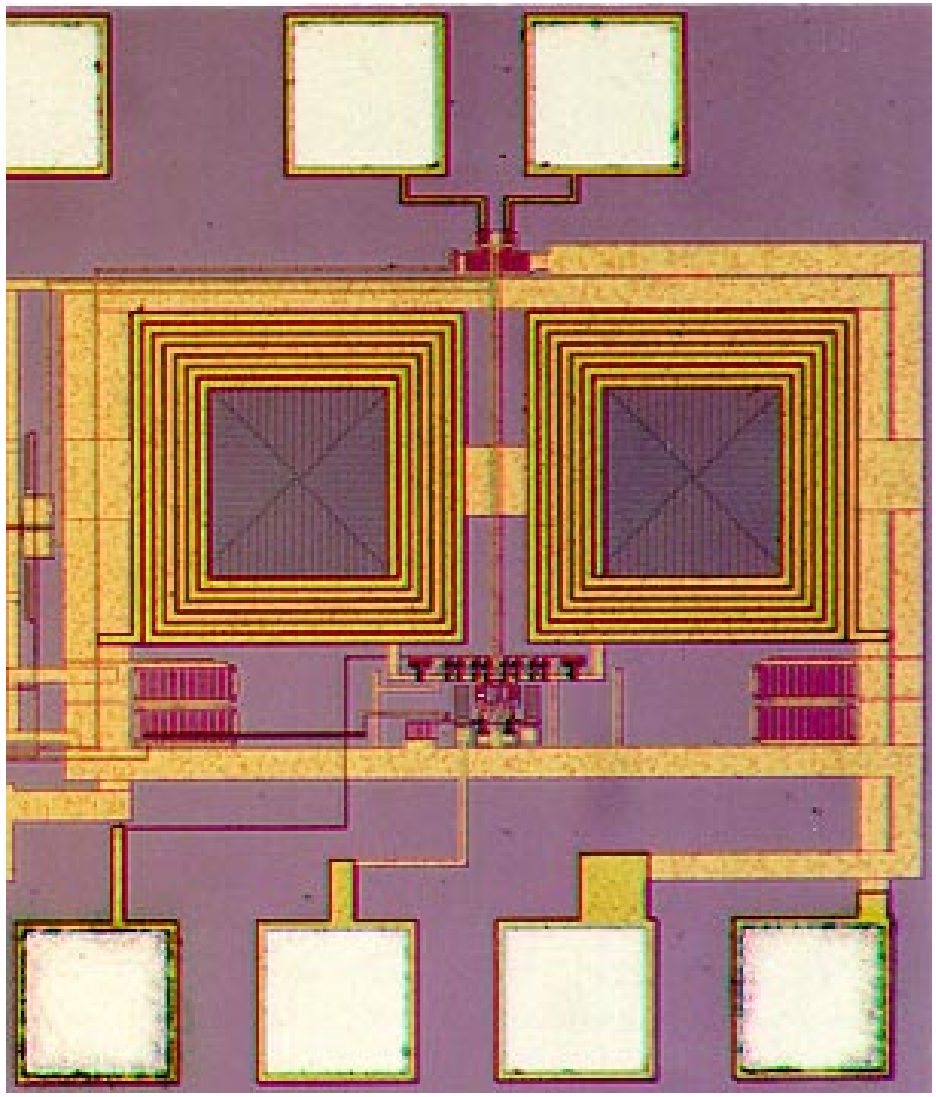


Chip micrograph

- 0.24μm CMOS
- area=0.186mm^2
  ($345\mu\text{m} \times 540\mu\text{m}$)



SUMMARY

maximum frequency of operation	5GHz
output frequency tuning	110MHz $\approx$ 5%
input–referred locking range	450MHz $\approx$ 10% @ 0.7mW
	900MHz $\approx$ 20% @ 1.0mW
technology	0.24μm CMOS
die area	0.186mm^2

flip–flop–based divider

0.24μm CMOS (simulation)	7mW @ 5GHz
0.1μm CMOS	2.6mW @ 5GHz

(Razavi *et al.*, JSSC Vol. 30, No.2, pp 101–109, Feb. 1995)

CONCLUSION

- injection–locked frequency dividers can be designed with:
  - very large locking range
  - very low power consumption
- spiral inductor design can be optimized to increase the ILFD locking range
- varactors can be used to extend the ILFD locking range (tracking ILFD)
- voltage–controlled ILFDs are suitable for low–power and high–frequency wireless systems

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