Monolithic Inductors for Silicon Radio Frequency Integrated Circuits

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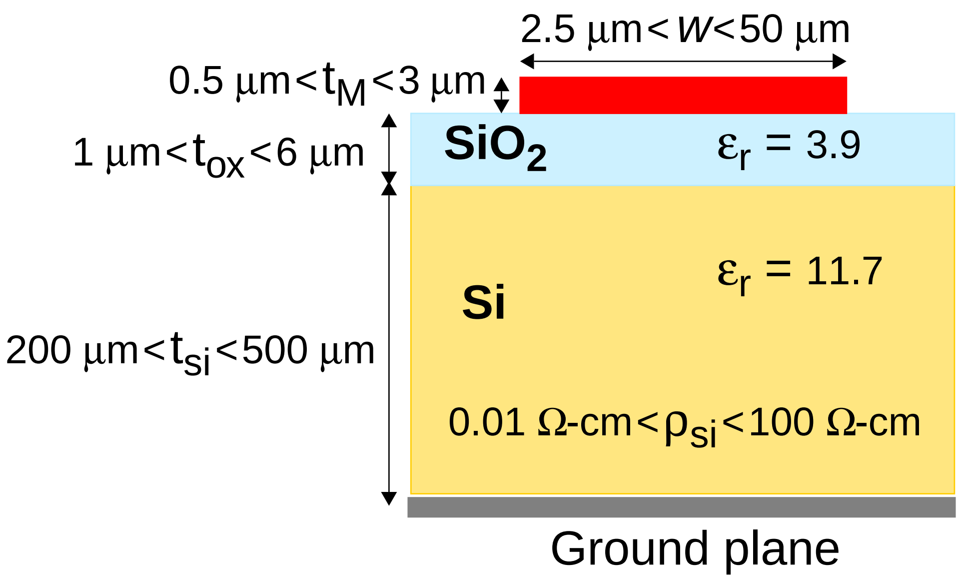
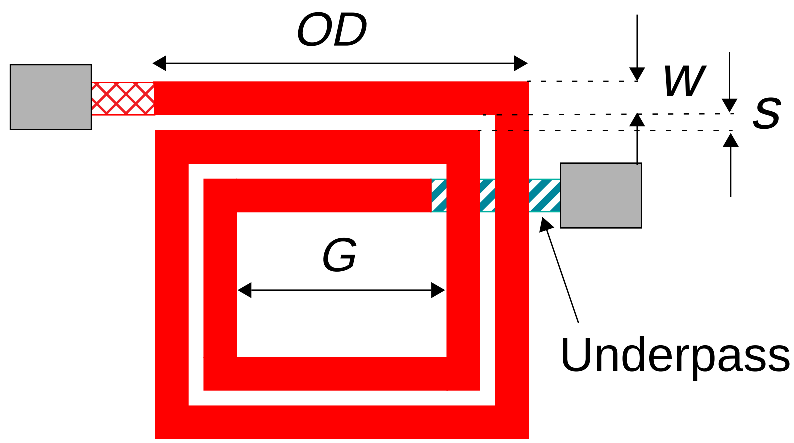
Outline

- Introduction
- Microstrip lines on silicon
- Spiral inductor modeling
- Differential excitation
- Symmetric spiral inductors
- Application: oscillator design
- Conclusion

Monolithic Inductors for Si RF Applications





Rectangular spiral inductor

LOW *Q-factor*

$Q_{typical} < 10$

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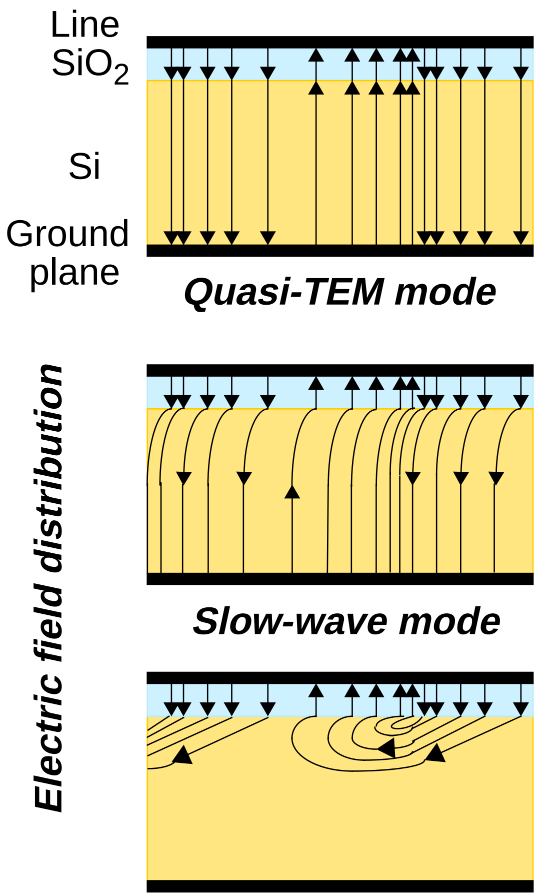
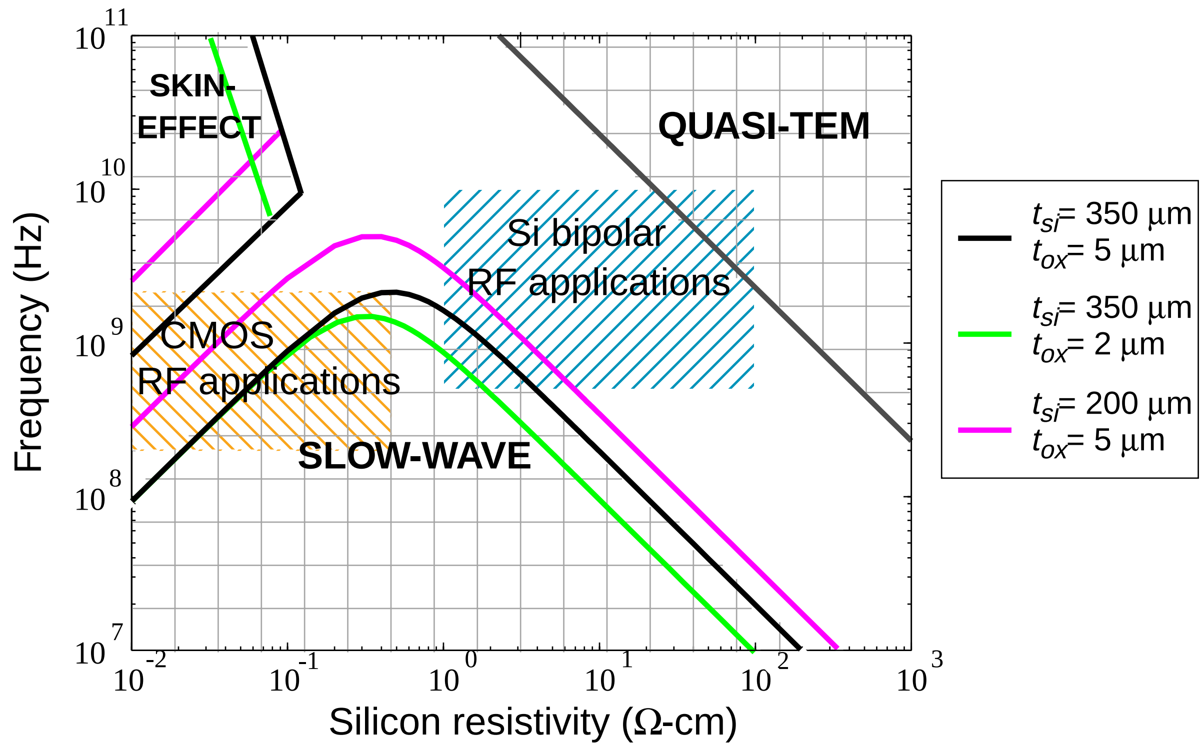
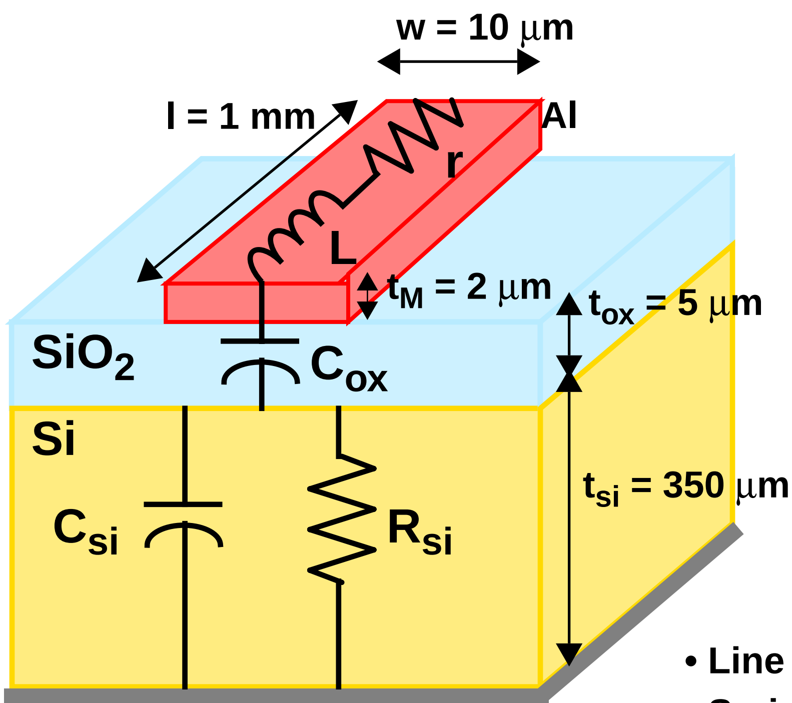
Propagation Modes

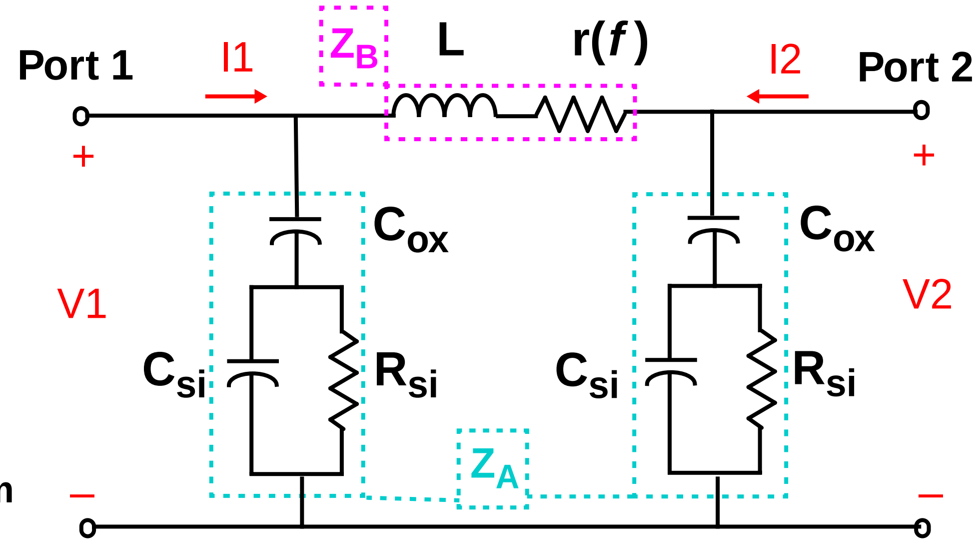




Frequency-resistivity mode chart

Microstrip Line Modeling

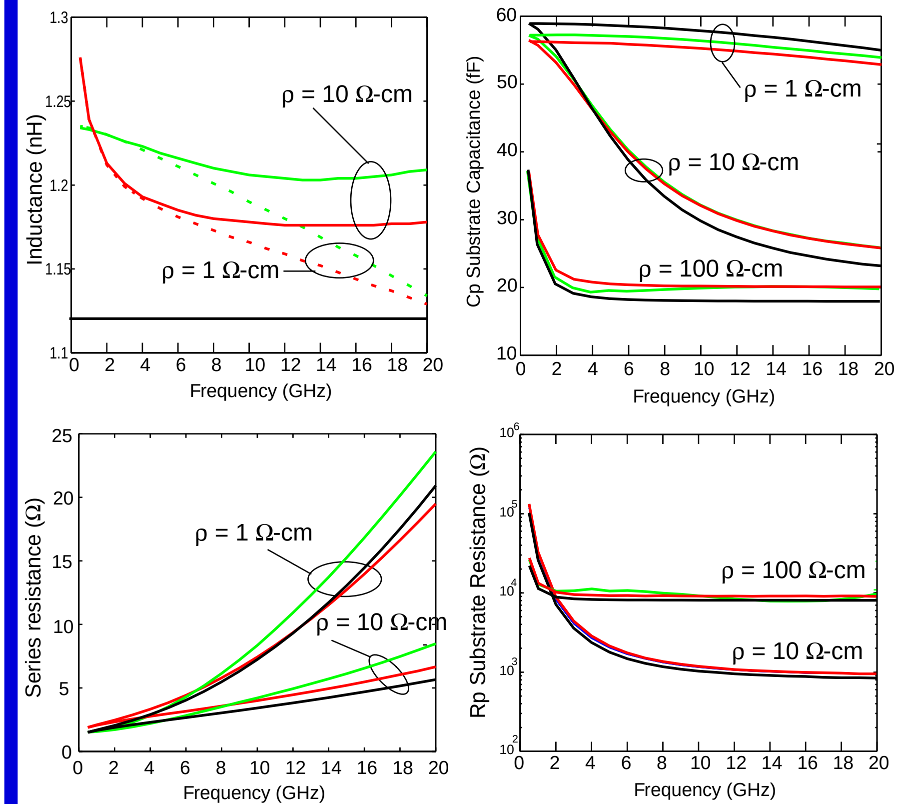




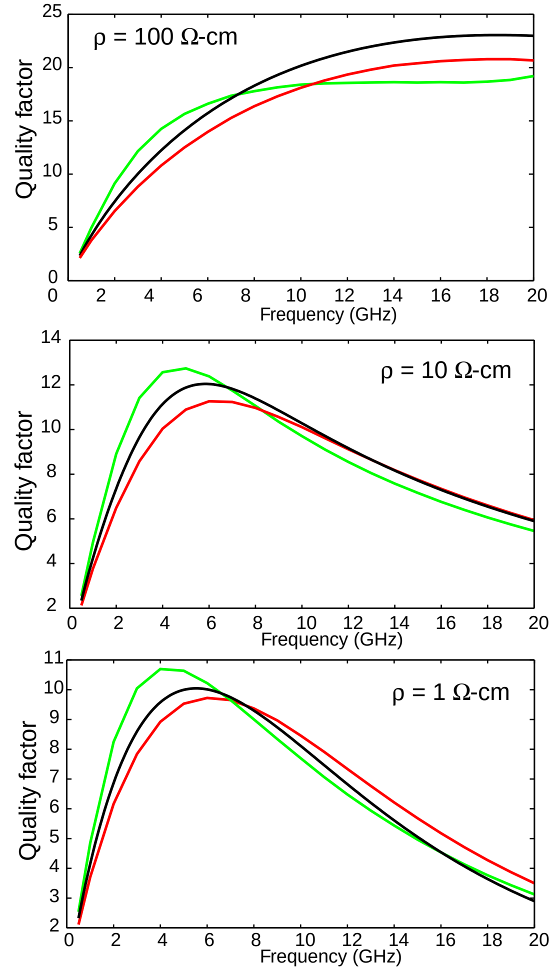
Lumped element equivalent circuit

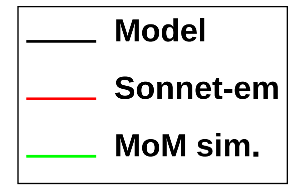
- **Line inductance**
- **Series resistance: skin-effect, conduction current in Si**
- **Cox } line-to-ground capacitance, extracted seperately with**
- **Csi } 2D numerical method for oxide and silicon layers**
- **Rsi:** $R_{si} = \dfrac{\varepsilon_{si} \cdot \rho_{si}}{C_{si}} \ (\Omega)$

Microstrip Line Modeling



Transmission line distributed parameters





Quality-factor

$$Q = \frac{1}{\mathbf{Re}[Y_{in}] \cdot \omega L_p}$$

below the first self-resonant frequency

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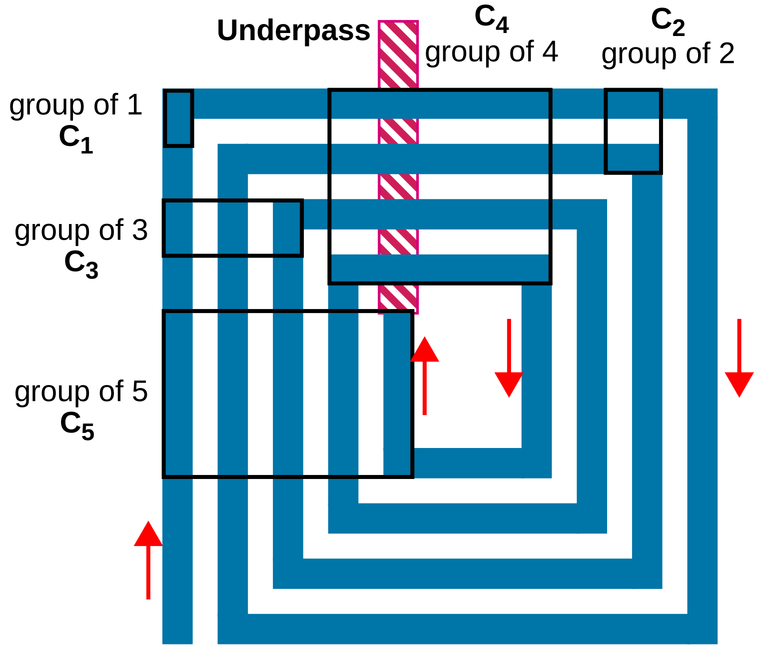
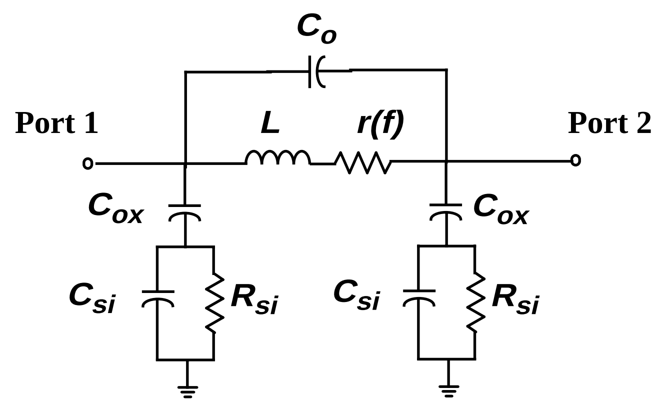
Spiral Inductor Modeling



- **Substrate capacitance**

$$\begin{matrix} C_{ox} \\ C_{si} \end{matrix} \quad \alpha \; (C5, C4, C3, C2, C1; w+s)$$

- C_o — **Line-to-line interwinding capacitance**
  Underpass parallel-plate capacitance



Inductor compact model

- **Inductance:**
  Summation of self- and mutual inductances
- **Series resistance**
  r(*f*) - **Metallization** $\alpha\ f^{-1/2}$
  - **Conductive Si** $\alpha\ f^{2}$
- **Silicon substrate resistance**

$$R_{si} = \frac{2 \cdot \varepsilon_{si} \cdot \rho_{si}}{C_{si}} \quad (\Omega)$$

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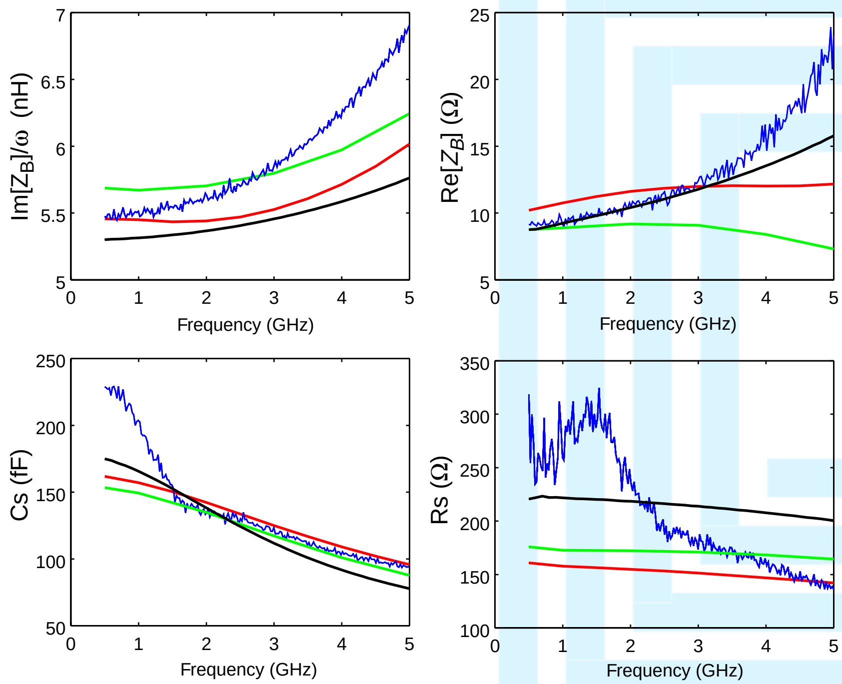
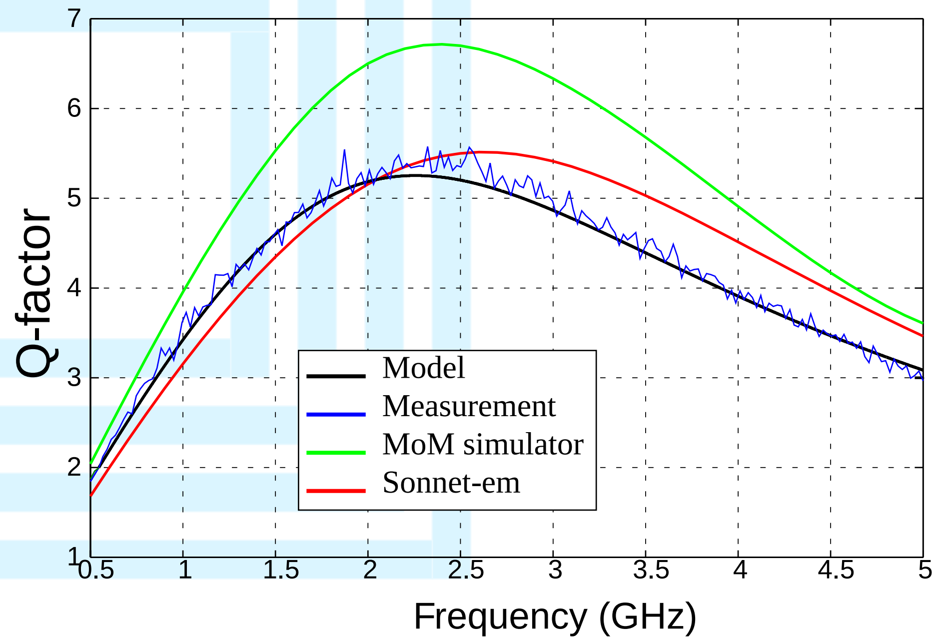
Spiral Inductor Modeling

4.5 turns, OD = 241 µm, w = 10 µm, s = 5 µm square spiral inductor

Table 1: Inductor Model Lumped elements

L (nH)	R_{dc} (Ω)	C_{ox} (fF)	C_{si} (fF)	R_{si} (Ω)	C_o (fF)
5.3	**8.7**	**178**	**45**	**229**	**15**





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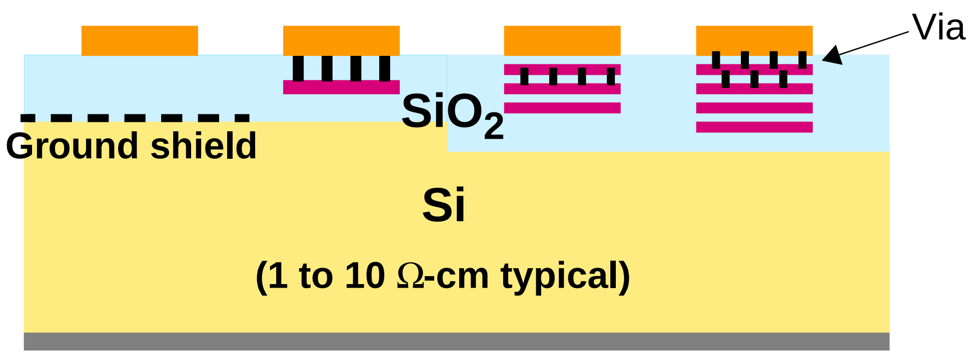
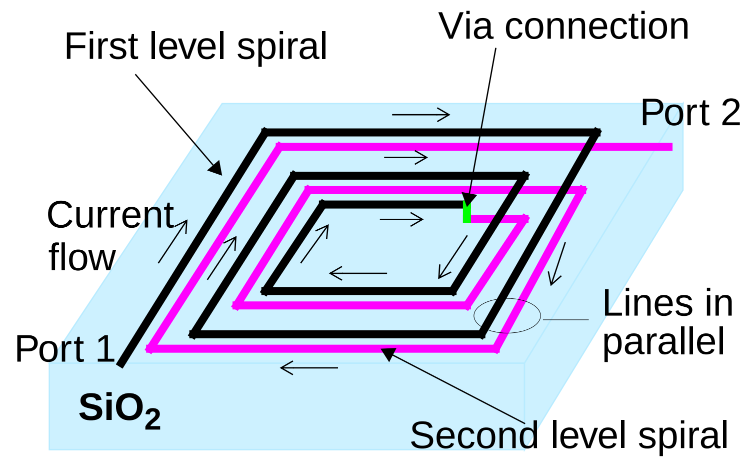
Inductor Realizations in Si

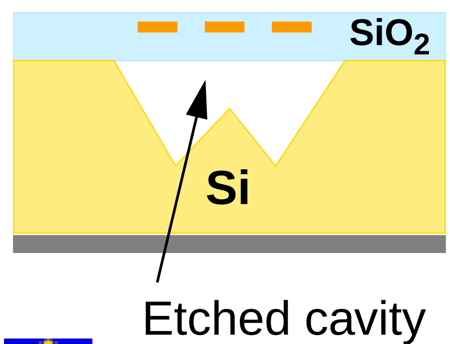
MIS

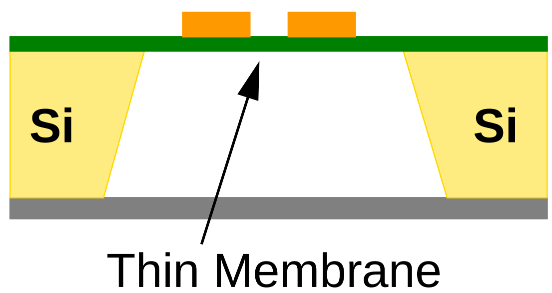
Metal Stacking

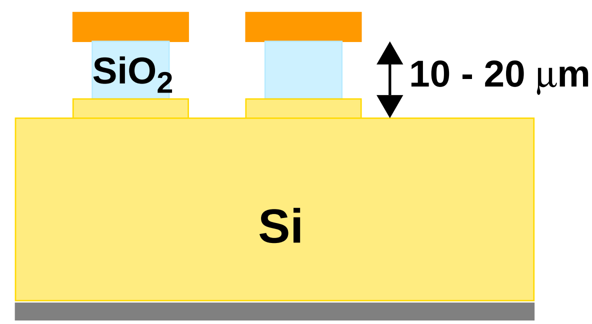




Alternate structures







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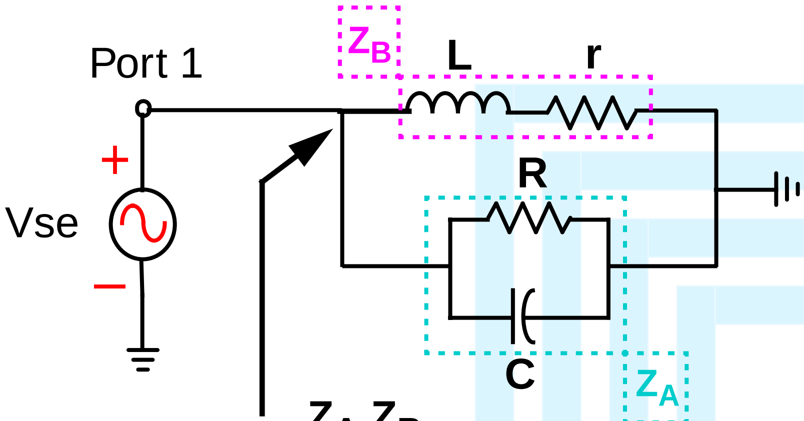
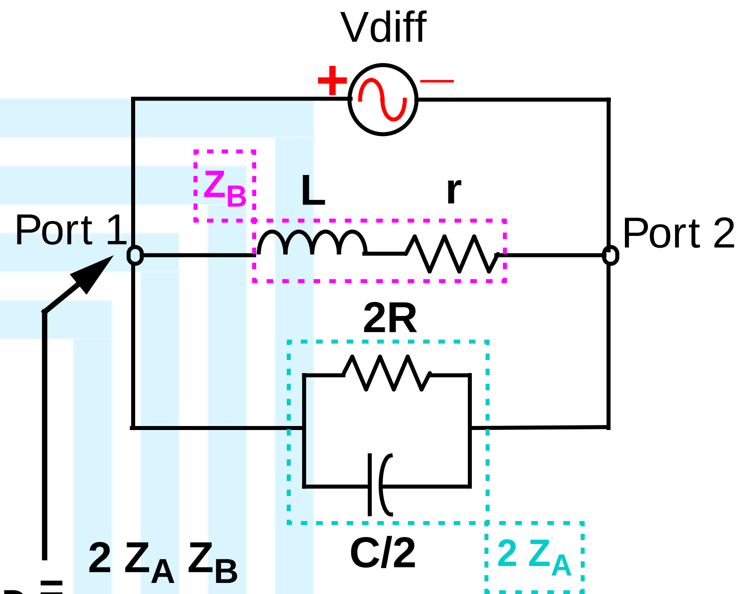
Single-ended / Differential Excitation



$$Z_{SE} = \frac{Z_A\,Z_B}{Z_A+Z_B}$$

Single-ended model



$$Z_D = \frac{2\,Z_A\,Z_B}{2\,Z_A+Z_B}$$

Differential model

- **Low frequencies (<1 GHz)**

  $Z_{differential} \approx Z_{single\text{-}ended}$

- **Higher frequencies:** **increasing influence of substrate parasitics**

  Re [$Z_{differential}$] < Re [$Z_{single\text{-}ended}$]

Differential excitation: Higher Q and broader bandwidth

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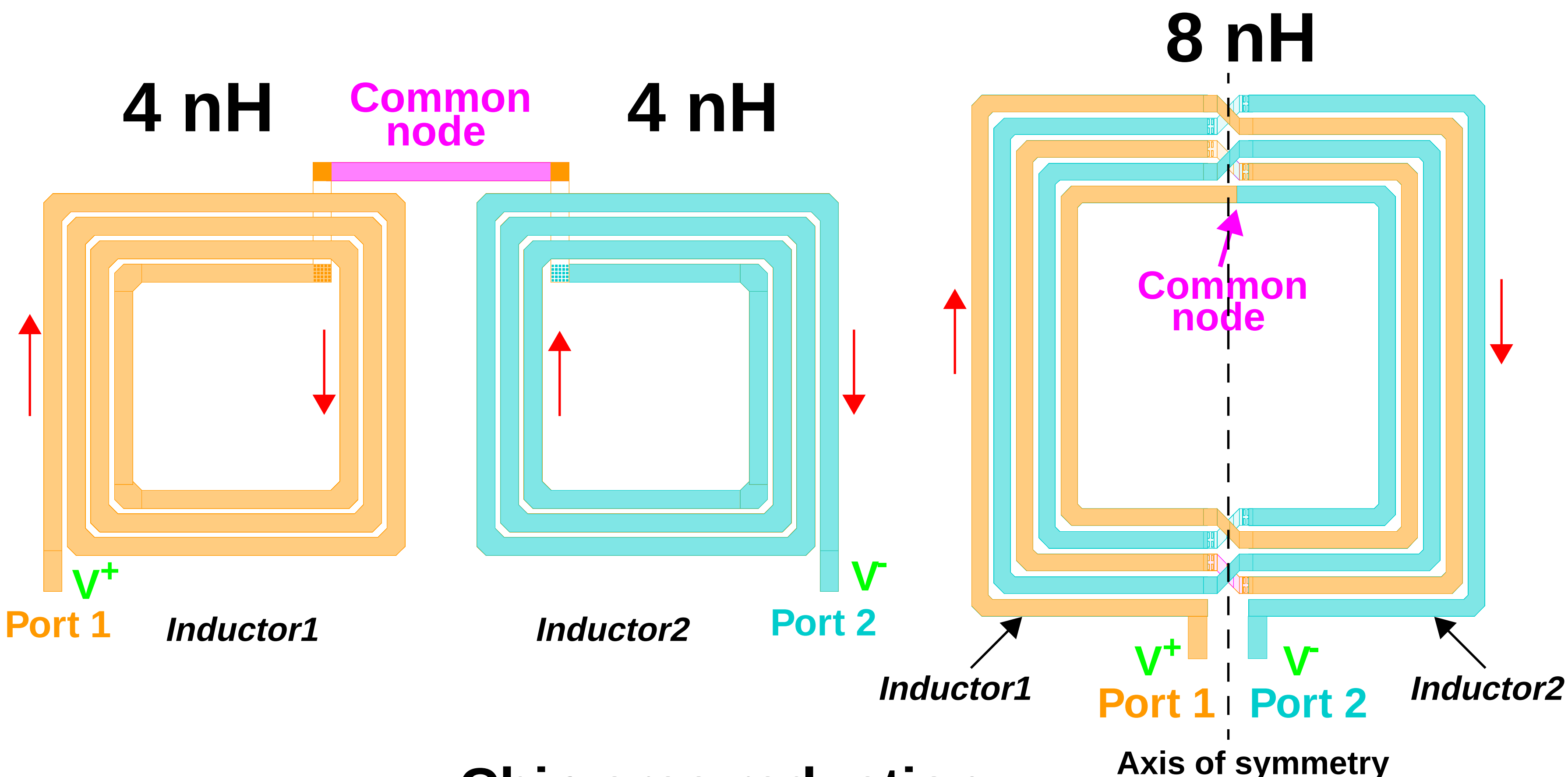
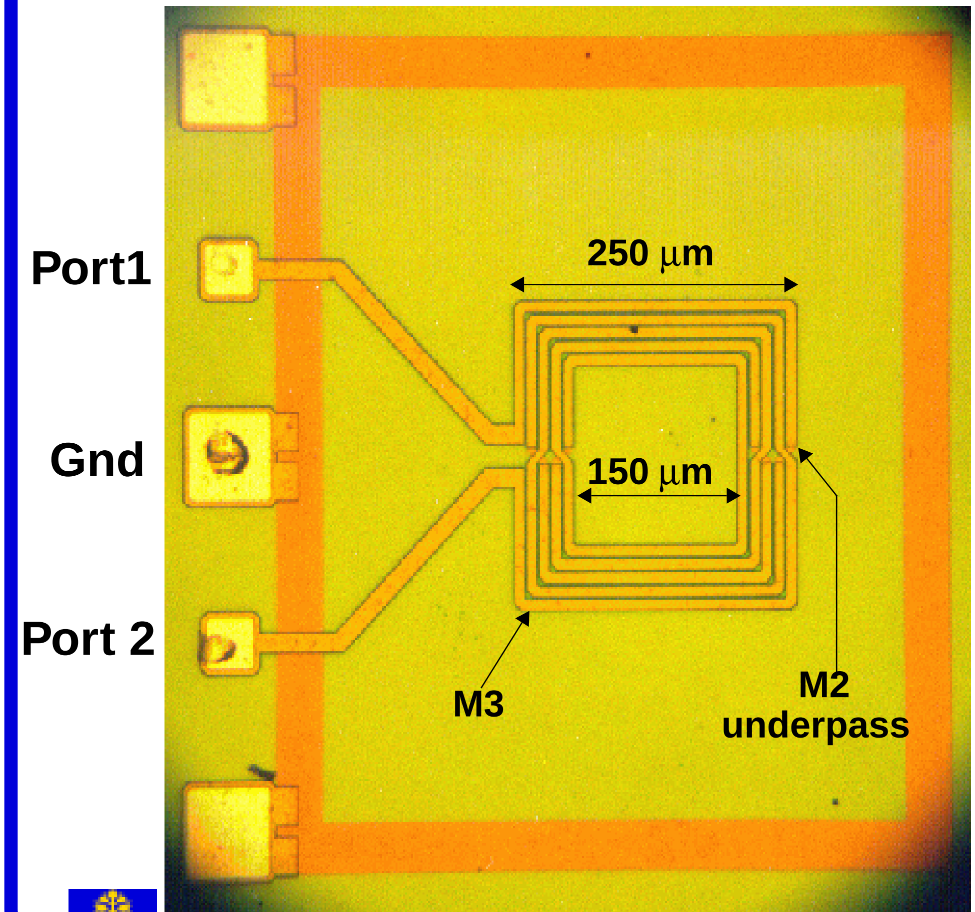
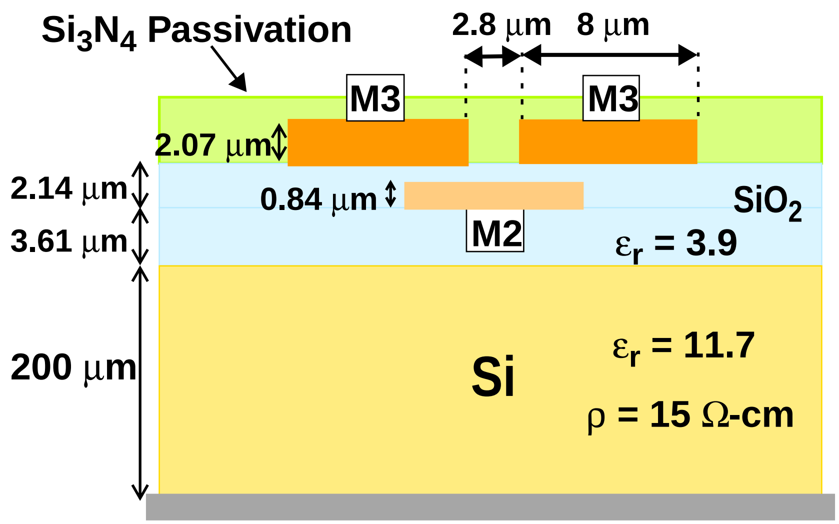
Asymmetrical vs. Symmetrical



Chip area reduction

Symmetrical Spiral Inductor





Partial cross-sectional view of inductor

Model / Simulation / Measurement

- **Symmetric inductor modeling**

Table 2: Symmetric Inductor Lumped Elements

L (nH)	R_{dc} (Ω)	C_{ox} (fF)	C_{si} (fF)	R_{si} (Ω)	C_o (fF)
8	7.5	146	52.7	590	52

- **Full-wave EM simulation**
- **Measurement**

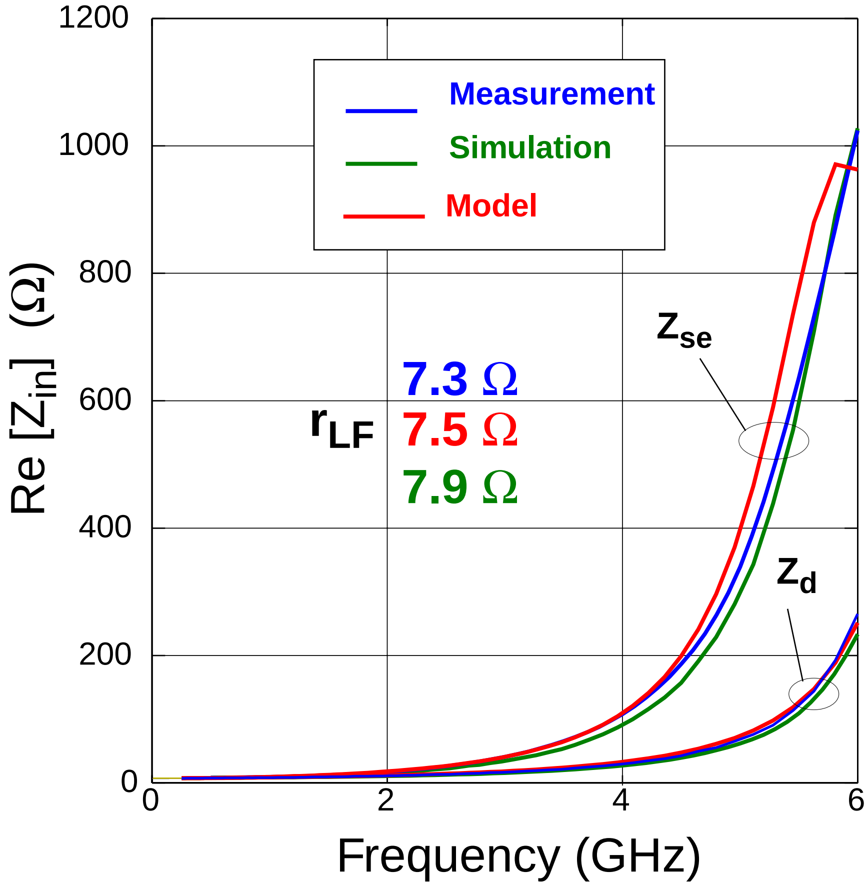
2-port calibration:

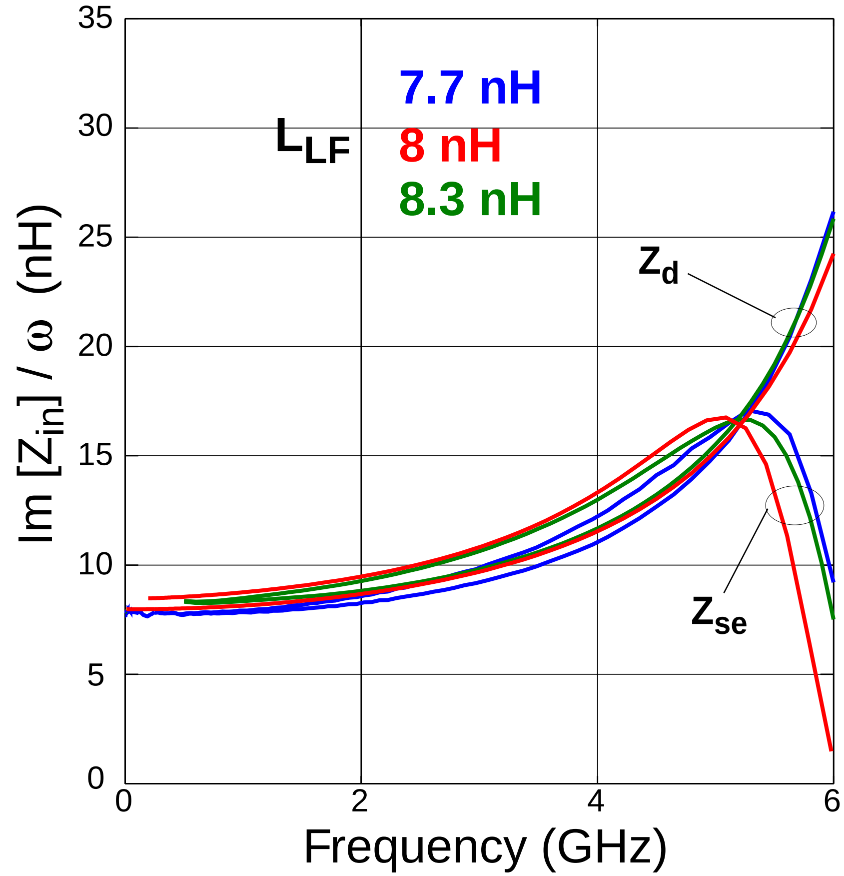
- **Probes on opposing sides for thru calibration**
- **Probes moved to same side for measurement**

De-embedding: Open / Short

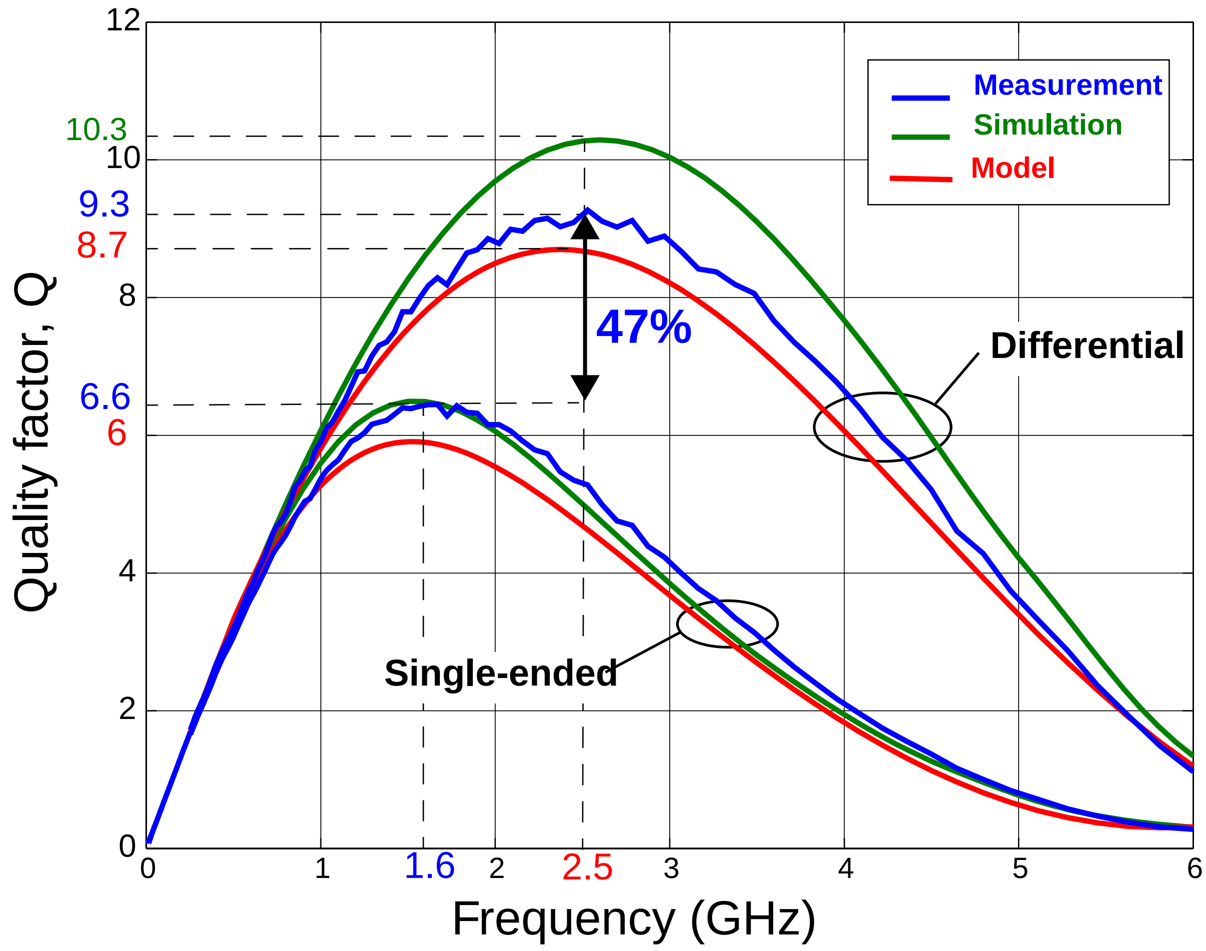
- **Differential:** $$S_d = \frac{S_{11} + S_{22} - S_{12} - S_{21}}{2}$$
- **Input impedance:** $$Z_d = 2Z_o\left(\frac{1 + S_d}{1 - S_d}\right)$$ (Z_0 = 50 Ω)

Input Impedance





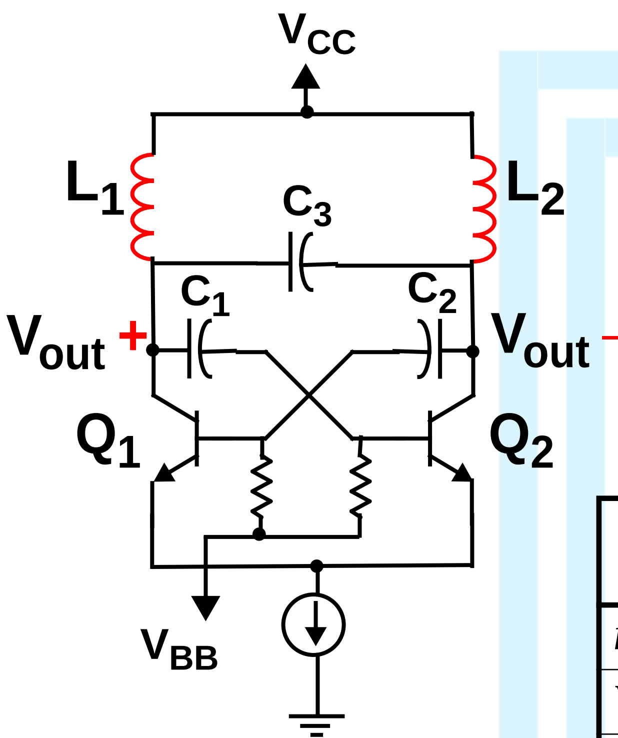
Quality Factor



Literature Comparison

Inductor type	*Reference*	*Si* ρ	t_M (μm)	*L (nH)*	*Q-factor*
1-level metal	Long	10 Ω-cm	1-3	1.88	6-10 @ 4 GHz
2-level metal	Park	2 kΩ-cm	2	13	12 @ 3 GHz
5-level metal	Burghartz	12 Ω-cm	4.3	2.2	16 @ 2 GHz
Ground shield	Yue	10-20 Ω-cm	2	8	7.2 @ 1.5 GHz
Membrane	Chi	2 kΩ-cm	1 (Au)	0.9 1.2	20 @ 4.3 GHz Res. freq: 70 GHz
Etched oxide/Si	Rieh	10 kΩ-cm		2	Res. freq: 30 GHz
Differential Single-ended	Danesh Long	15 Ω-cm	2	8	9.3 @ 2.5 GHz 6.6 @ 1.6 GHz

Application: Differential Oscillator



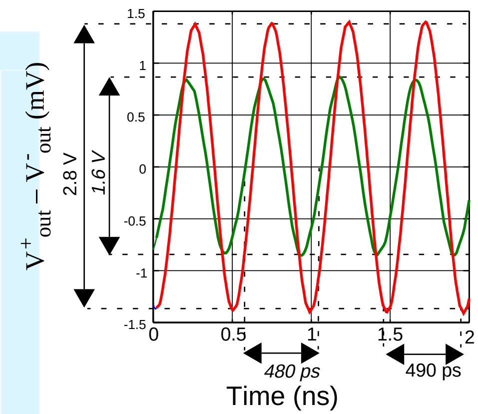
Cross-coupled Oscillator

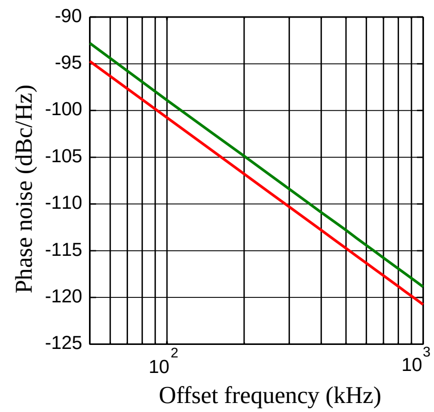
Table 3: Comparison between inductors.

Characteristics	**8 nH symmetric**	**4 nH asymmetric**
OD / N	250 µm / 5	210 µm / 3.5
Inner gap	150 µm	140 µm
Total length	4 mm	2.44 mm
R_{dc}	7.5 Ω	4.56 Ω
***Q* @ 2.1 GHz**	**8.6**	**7.5**

Table 4: Comparison of overall performance.

Parameters	**8 nH symmetric**	**4 nH asymmetric**
f_{osc} (GHz)	**2.061**	**2.114**
V_{out} swing (V)	**2.8**	**1.6**
PN (dBc/Hz) @ 1 MHz	**-120.9**	**-118.9**
P_{out} (dBm)	7.1	5.4
3rd harmonic P_{out} (dBm)	-30.9	-29.1





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Conclusion

- Propagation modes for silicon substrates
- Microstrip line and spiral inductor modeling
- Differential vs single-ended excitation: lower parasitics
  - Higher peak Q-factor (50% +)
  - Higher peak frequency (50% +)
  - Broader operating bandwidth
- RF applications
  - Symmetric inductors (reduced chip area)
  - Oscillators, amplifiers, mixers ...
  - Other substrates: GaAs