A Q-Factor Enhancement Technique for MMIC Inductors

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Outline

- Introduction
- Differential excitation for higher Q-factor realization
- Symmetric spiral inductors
- Results
- Applications
- Conclusion

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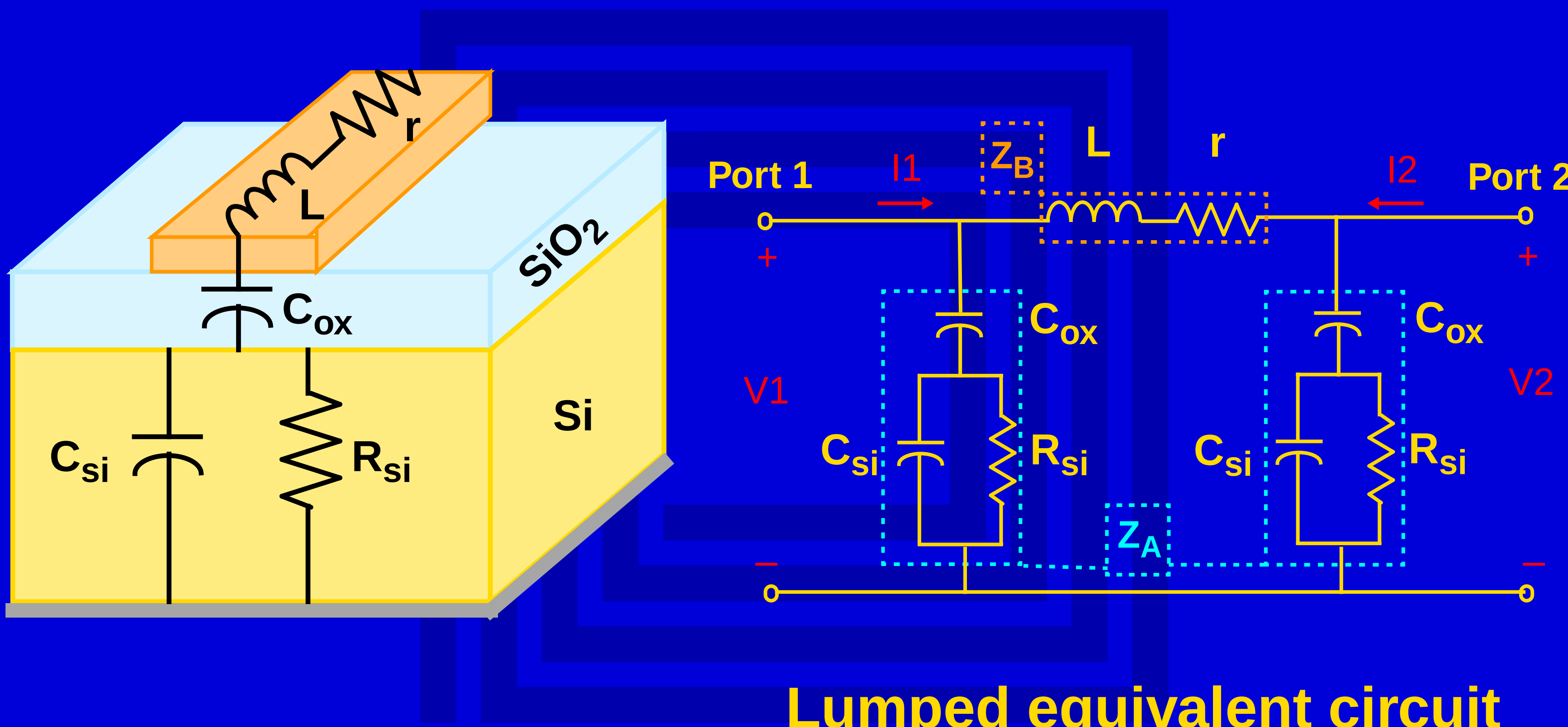
Microstrip Line Modeling



Lumped equivalent circuit

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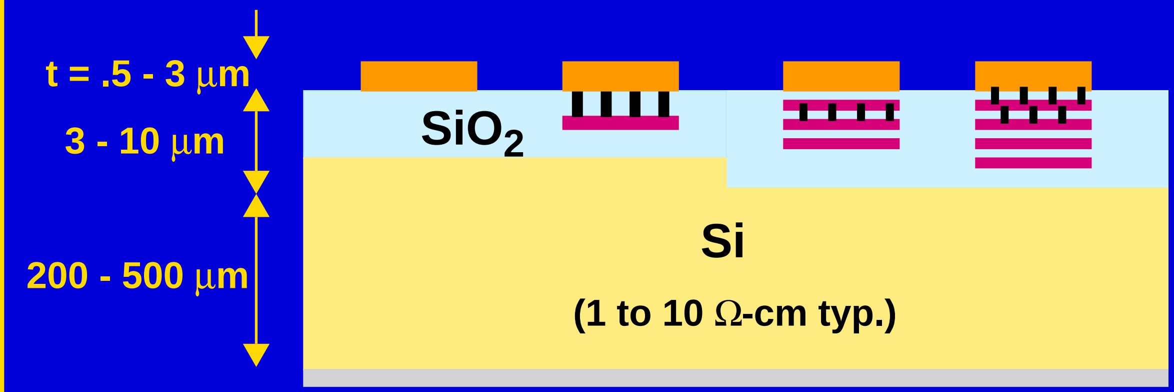
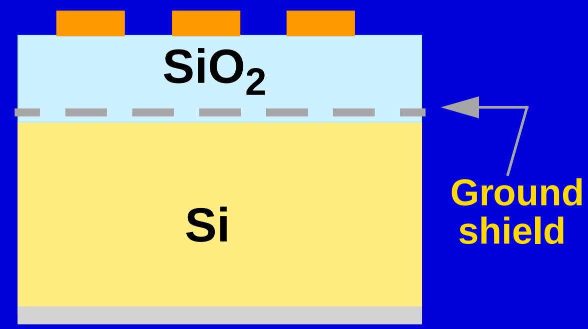
Inductor Realizations in Si

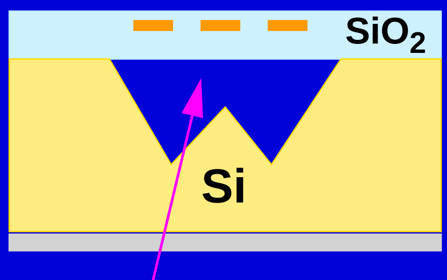
MIS



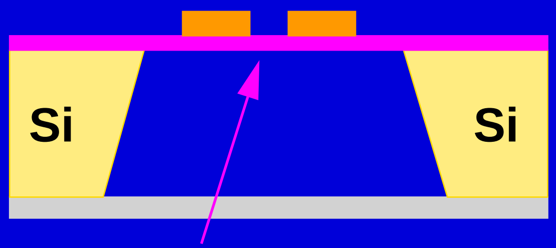
MIS + Ground shield



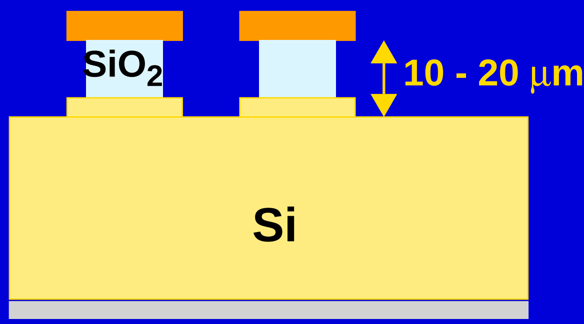
Alternate structures



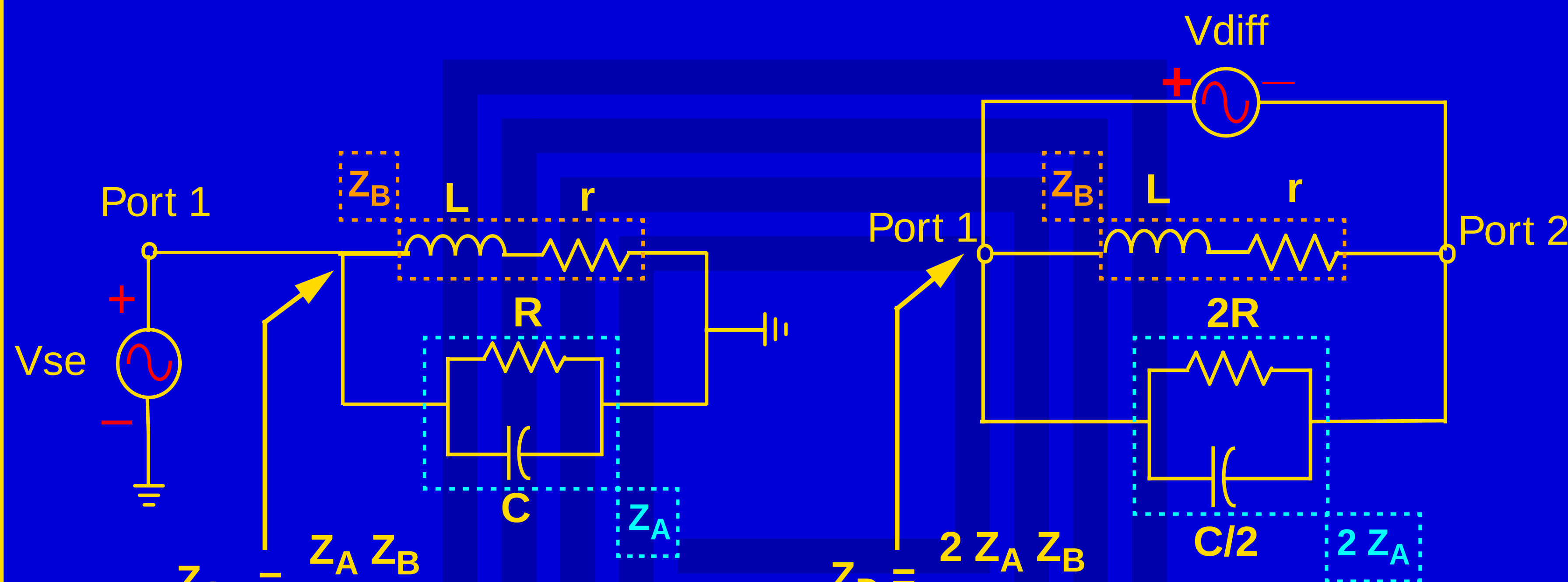
Etched cavity



Thin Membrane



Single-ended / Differential Excitation



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

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

Single-ended model

Differential model

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Quality Factor

Below first resonant frequency of inductor

$$Q = \frac{2\pi fL}{Re[Z_{input}]}$$

- **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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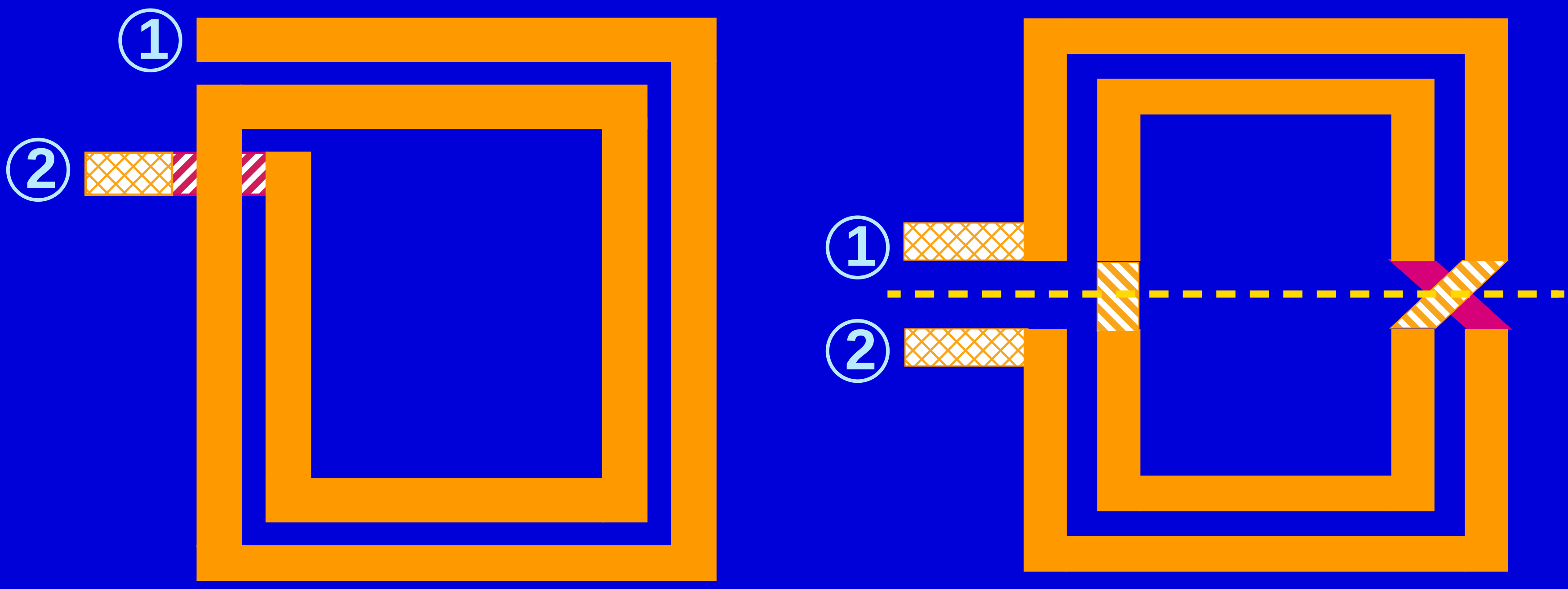
Asymmetrical vs Symmetrical



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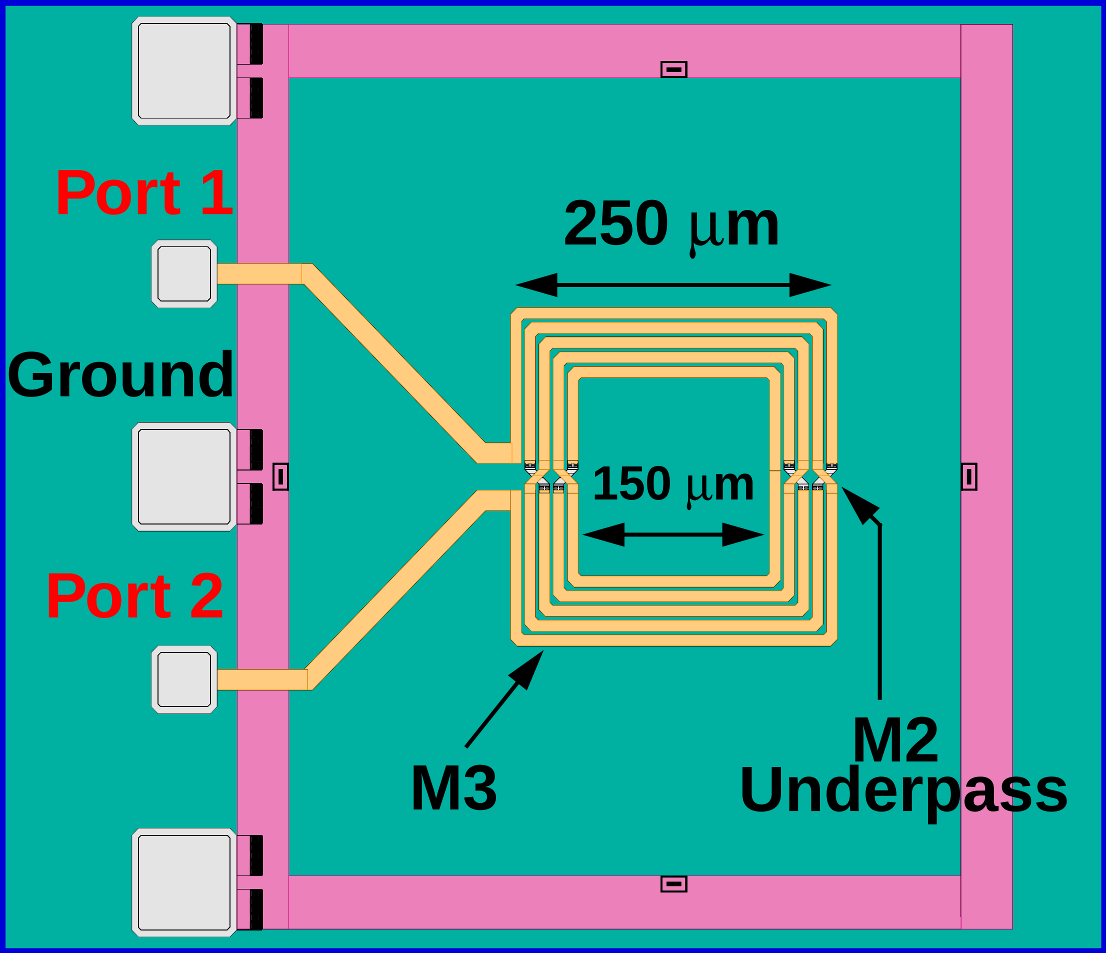
Symmetrical Spiral Inductor



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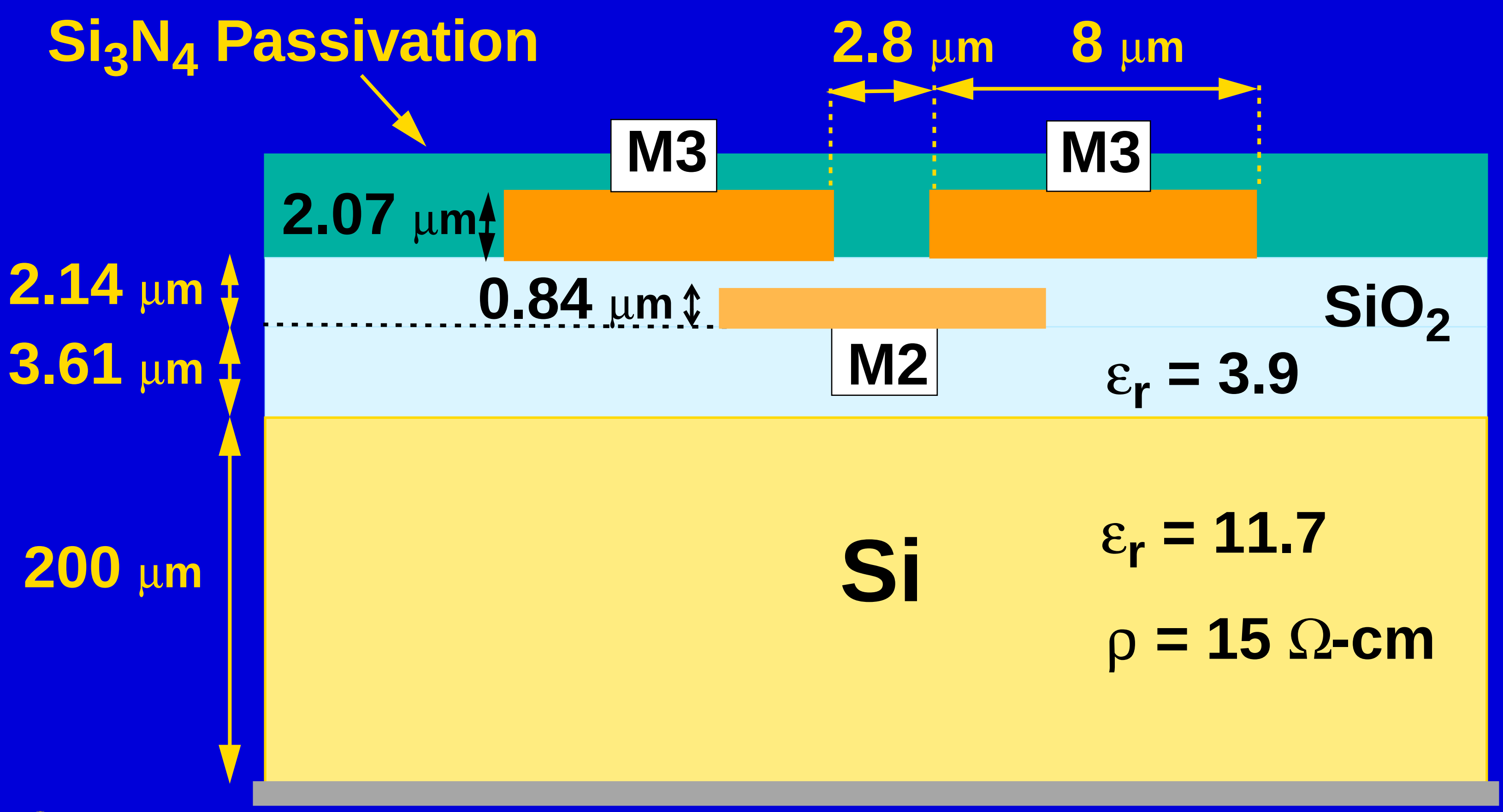
Technology



Si3N4 Passivation
2.8 µm
8 µm
M3
M3
2.07 µm
2.14 µm
0.84 µm
SiO2
3.61 µm
M2
εr = 3.9
200 µm
Si
εr = 11.7
ρ = 15 Ω-cm

Simulation / Measurement

- Full-wave EM simulation
- Measurement

  2-port calibration:

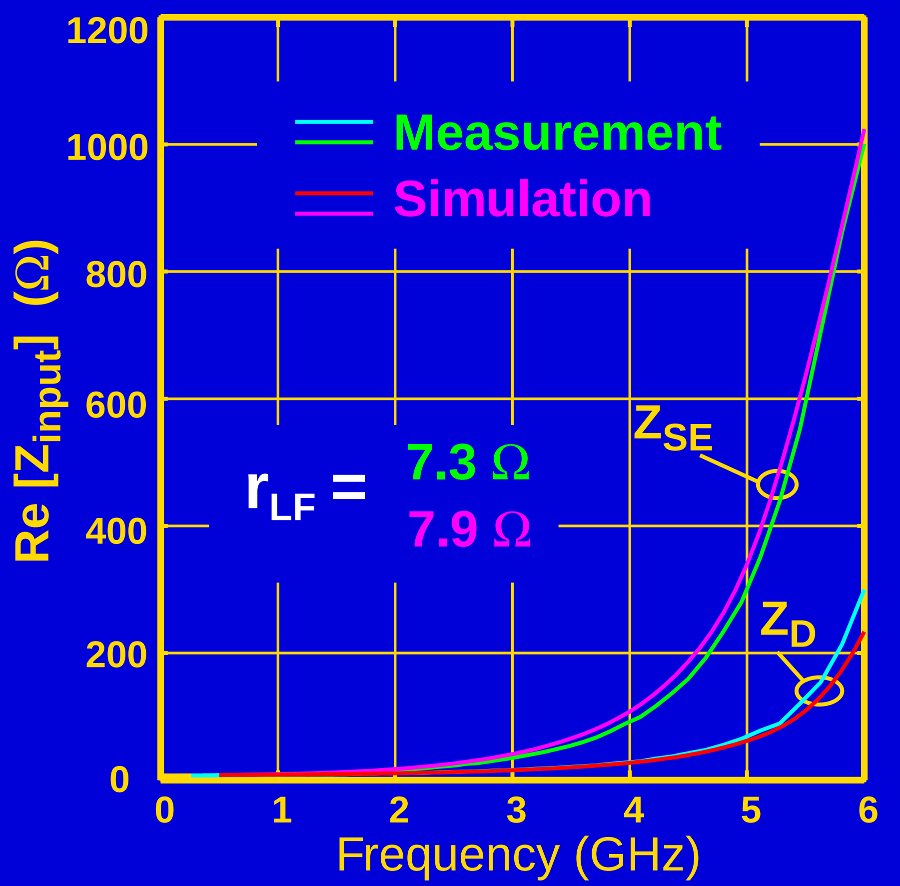
  - Probes on opposing sides for thru calibration
  - Probes moved to same side for measurement

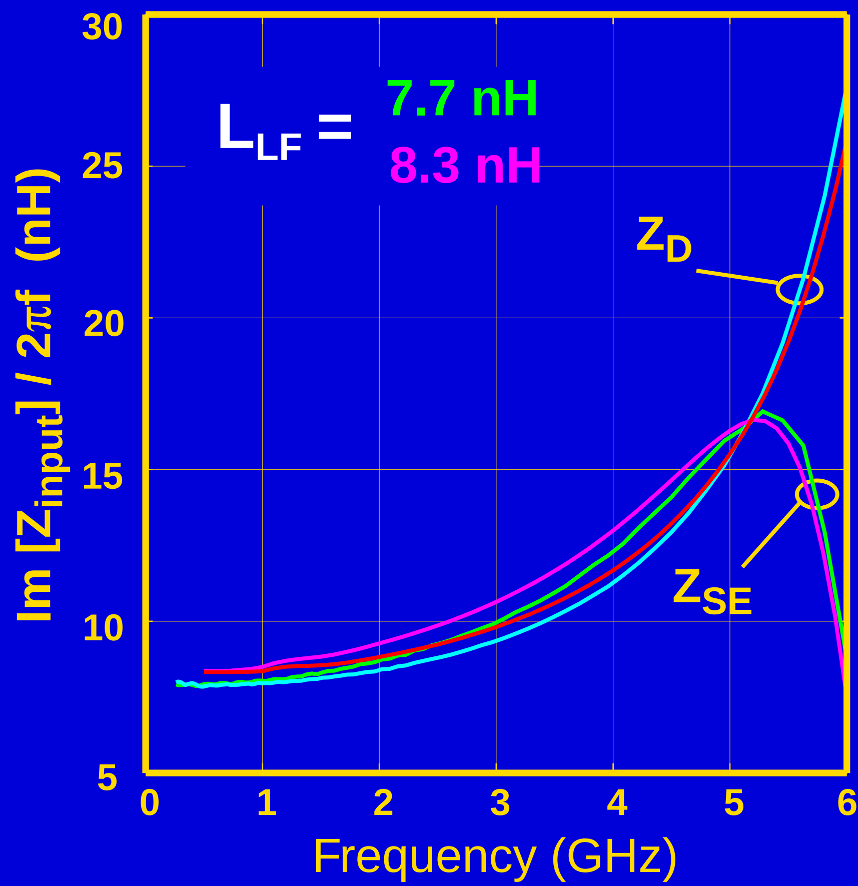
  De-embedding: Open / Short

- Differential: $S_D = S_{11} - S_{21}$

  Input impedance: $Z_D = Z_0\left(\frac{1 + S_D}{1 - S_D}\right)$ $(Z_0 = 100\ \Omega)$

Input Impedance





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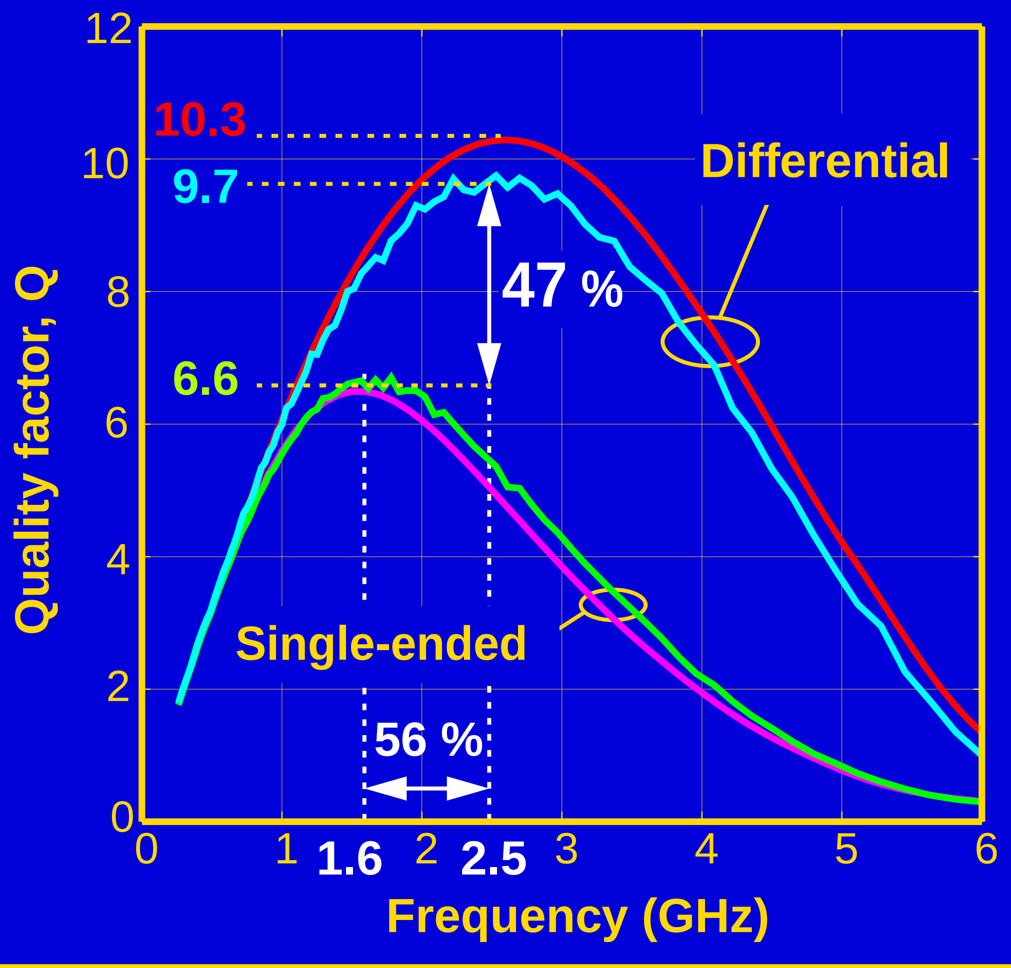
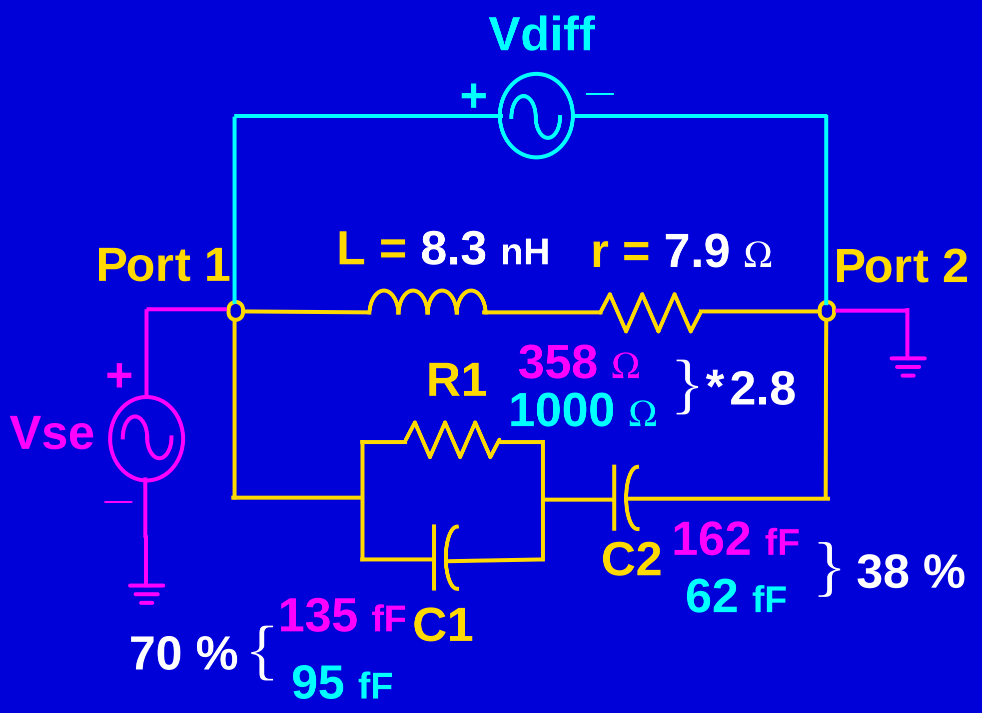
Quality factor



Equivalent Circuit Model



Broadband parameter fit
(0.5 - 6 GHz)

Measurement Errors

- **Topmetal thickness**

  t_{M3} + 10% = 2.27 μm ⟶ r = 7.5 Ω (Meas: 7.3 Ω)

- **NA accuracy:** connectors, cables, temperature, frequency drifts
- **Calibration**
- **De-embedding error**

  Probe resistance (r = 0.3 Ω)

  Parasitics of open / short interconnects and pads

  C = 63 fF @ 2 GHz / L = 250 pH, r = 0.24 Ω

- **Parameter variation**

  Si resistivity

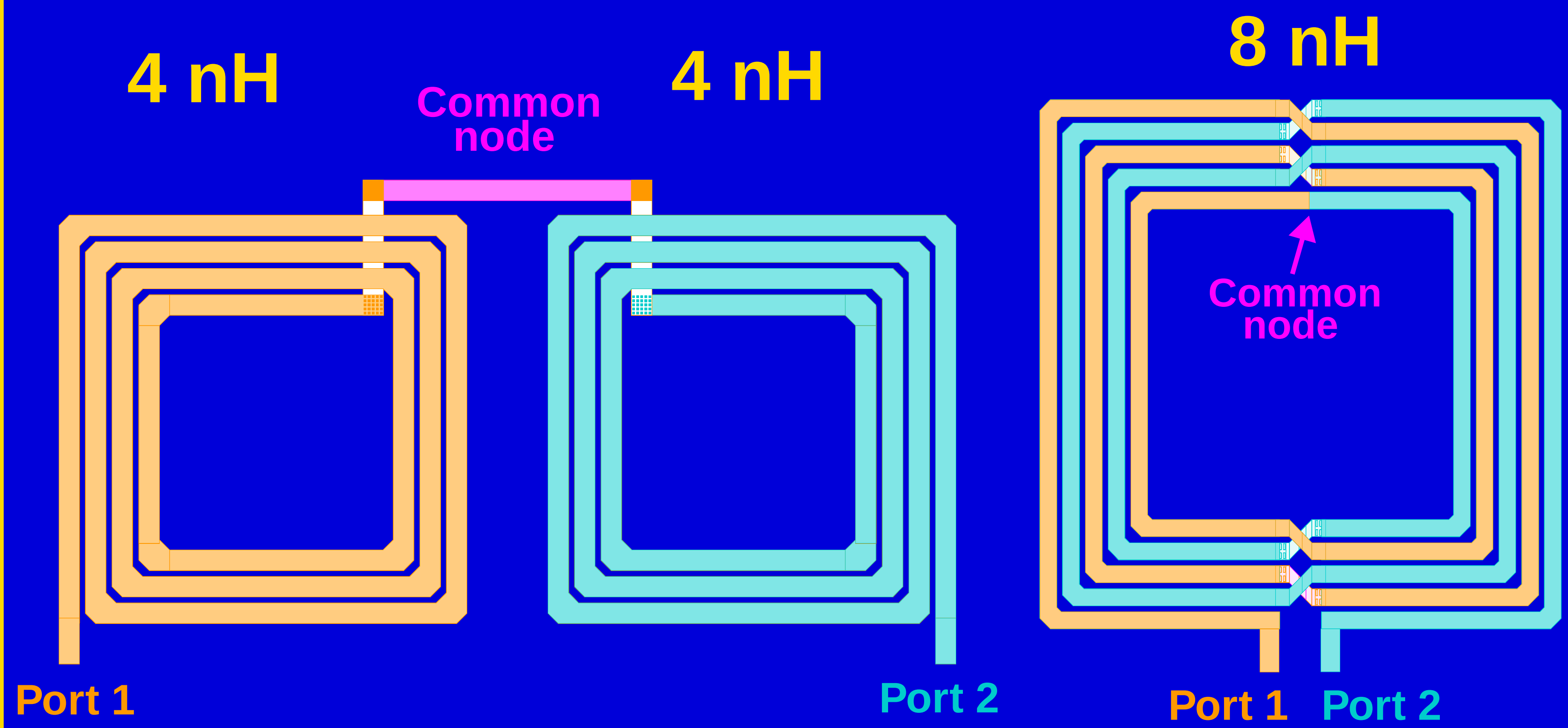
  Layer thickness, width, spacing

  Temperature

Results

Inductor type	Reference	Si ρ	t (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 Symmetrical	Danesh Long	15 Ω-cm	2	8	9.7 @ 2.5 GHz

Layout comparison



Chip area reduction

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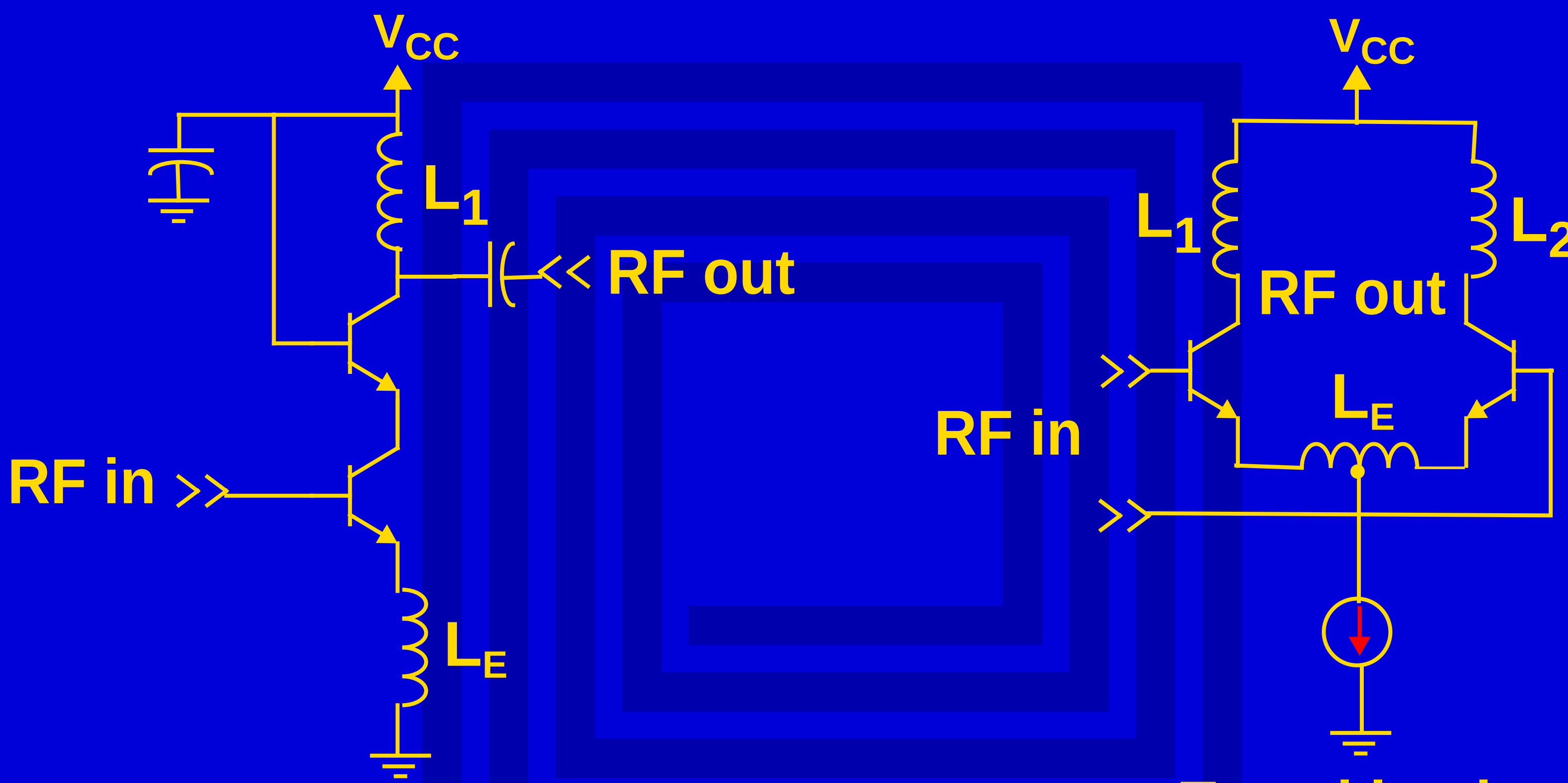
Amplifier



Single stage

Tuned loads
Inductor degeneration

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Conclusion

- Differential vs single-ended excitation: lower parasitics
  - Higher peak Q-factor (50% +)
  - Higher peak frequency (50% +)
  - Broader operating bandwidth
- RF applications
  - Symmetrical inductors (reduced chip area)
  - Oscillators, amplifiers, mixers ...
  - Other substrates: GaAs
- Monolithic circuits: extra components have small marginal cost

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