

Design and Fabrication of a Microwave Resonator Using Aluminum on Silicon for $50\ \Omega$ Impedance Matching

Nikos Koutsopoulos

June 2025

- Microwave resonators are key components in:
 - RF communication systems
 - Quantum information devices
 - Superconducting circuits
- Goal: Design a CPW resonator on silicon with aluminum metallization, matched to $50\ \Omega$
- Talk outline:
 - 1 Theory of transmission lines and resonators
 - 2 Fabrication via photolithography and lift-off
 - 3 COMSOL simulations and results

Transmission Line Fundamentals

- Distributed parameters: R, L, G, C
- Telegraphers' equations:

$$\frac{\partial V}{\partial z} = -RI - L\frac{\partial I}{\partial t}, \quad \frac{\partial I}{\partial z} = -GV - C\frac{\partial V}{\partial t}$$

- Wave equation (lossless):

$$\frac{\partial^2 V}{\partial z^2} = -\omega^2 LCV$$

- Characteristic impedance:

$$Z_0 = \sqrt{\frac{L}{C}} \quad (\text{lossless case})$$

- Matching condition: $Z_L = Z_0 \Rightarrow \Gamma = 0$

Coplanar Waveguide Geometry

- CPW = center conductor + side ground planes on same plane
- Quasi-TEM mode supported; fields confined between signal and ground
- No vias needed → planar fabrication
- Effective permittivity approximation:

$$\epsilon_{\text{eff}} \approx \frac{\epsilon_r + 1}{2}$$

Resonance and Impedance in CPWs

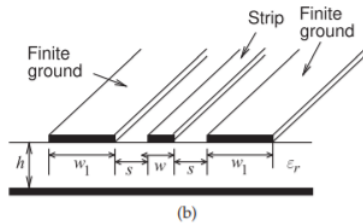
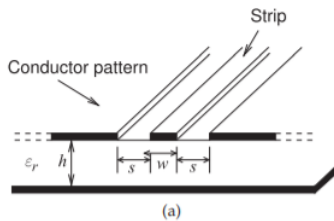
- Quarter-wave resonance:

$$f_0 = \frac{c}{4L\sqrt{\epsilon_{\text{eff}}}}$$

- Characteristic impedance:

$$Z_0 = \frac{30\pi}{\sqrt{\epsilon_{\text{eff}}}} \cdot \frac{K(k')}{K(k)}, \quad k = \frac{W}{W + 2S}$$

- $K(k)$: Complete elliptic integral of the first kind
- W = signal width, S = gap to ground



Coupling and Quality Factors

- Capacitive coupling used for excitation
- Quality factors:
 - Q_i : internal losses (metal, dielectric, radiation)
 - Q_e : coupling to feedline
 - Q_L : total (loaded) quality factor

$$\frac{1}{Q_L} = \frac{1}{Q_i} + \frac{1}{Q_e}$$

- $S_{11}(f)$ near resonance:

$$|S_{11}(f)| = \left| 1 - \frac{Q_L/Q_e}{1 + 2jQ_L \left(\frac{f-f_0}{f_0} \right)} \right|$$

Photolithography Process

- Start with RCA-cleaned high-resistivity silicon wafer; dehydration bake at 120°C
- Apply HMDS for adhesion promotion (vapor priming or spin coating)
- Spin-coat positive photoresist (e.g., S1813) at 4000 rpm for 1.3 μm thickness
- Prebake at 90–100°C to drive off solvents
- UV exposure through photomask (e.g., chrome-on-glass) using contact aligner
- Develop in aqueous alkaline developer (e.g., MF-319) to reveal pattern
- Optional: hard bake to increase resist durability during metal deposition

Lift-Off for Metal Patterning

- Bilayer resist stack: bottom LOR (e.g., LOR3A) + top photoresist (e.g., S1813)
- Development produces undercut profile for effective lift-off
- Aluminum deposited directionally over the pattern (thermal/e-beam evaporation)
- Immersion in acetone or NMP dissolves resist, lifting away unwanted metal
- Leaves clean, high-fidelity CPW geometry with sharp edges and defined gaps

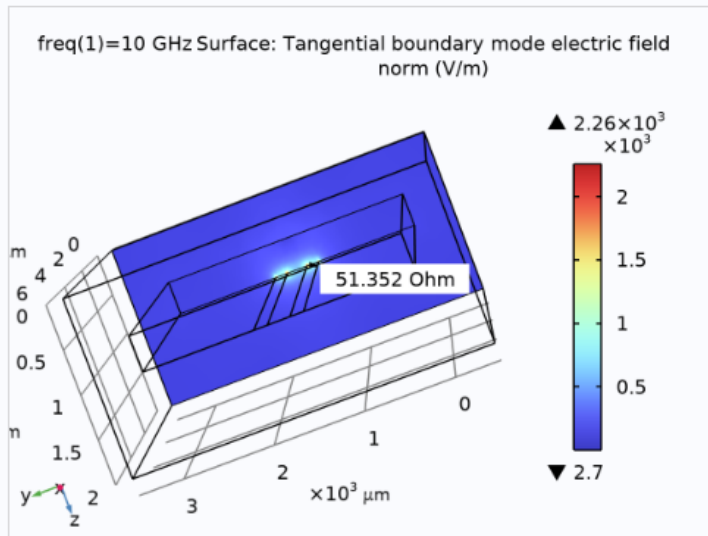
Aluminum Metallization

- Thermal or e-beam evaporation under vacuum
- Typical thickness: 100–200 nm
- Conductivity: $\rho = 2.65 \times 10^{-8} \Omega \cdot m$
- Skin depth at 5 GHz: $\sim 1 \mu m$
- Surface quality affects Q_i

Simulation Setup (COMSOL)

- CPW resonator on high-resistivity Si substrate ($\epsilon_r = 11.45$)
- Dimensions: $W = 250\ \mu\text{m}$, $S = 150\ \mu\text{m}$
- Substrate thickness: $400\ \mu\text{m}$
- Ports: Numeric ports with TEM field analysis
- Boundary conditions:
 - PEC for metal regions
 - Scattering boundaries for open space
- Simulation studies:
 - Eigenfrequency (resonance modes)
 - Frequency-domain sweep (S-parameters)

Simulations Results








Design Implications and Optimization

- Tunable Q_e via coupling gap and overlap
- Geometry determines Z_0 and ϵ_{eff}
- Applications:
 - Qubit readout resonators
 - Filters in RF circuits
 - Surface-sensitive sensing

Summary

- CPW resonator on silicon designed for $50\ \Omega$
- Photolithography + aluminum lift-off used
- Simulations confirm resonant behavior and impedance match
- Ready for fabrication and cryogenic measurements

References I

-  Pozar, D. M., *Microwave Engineering*, 4th Ed., Wiley, 2012.
-  Göppl, M., et al., *Coplanar waveguide resonators for circuit quantum electrodynamics*, J. Appl. Phys. 104, 113904 (2008).
-  Steer, M., *Microwave and RF Design: A Systems Approach*, North Carolina State University, 2019.
-  Madou, M. J., *Manufacturing Techniques for Microfabrication and Nanotechnology*, 3rd Ed., CRC Press, 2018.
-  Franssila, S., *Introduction to Microfabrication*, 2nd Ed., Wiley, 2010.



Steer, M., *Co-Planar Waveguide*, in *Microwave and RF Design II - Transmission Lines*, LibreTexts,
newline[https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_\(Steer\)/03%3A_Planar_Transmission_Lines/3.08%3A_Co-Planar_Waveguide](https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_(Steer)/03%3A_Planar_Transmission_Lines/3.08%3A_Co-Planar_Waveguide)

Thank You!