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CMOS-Compatible MIM Metamaterial Absorbers for Spectrally Selective LWIR Thermal Sensors

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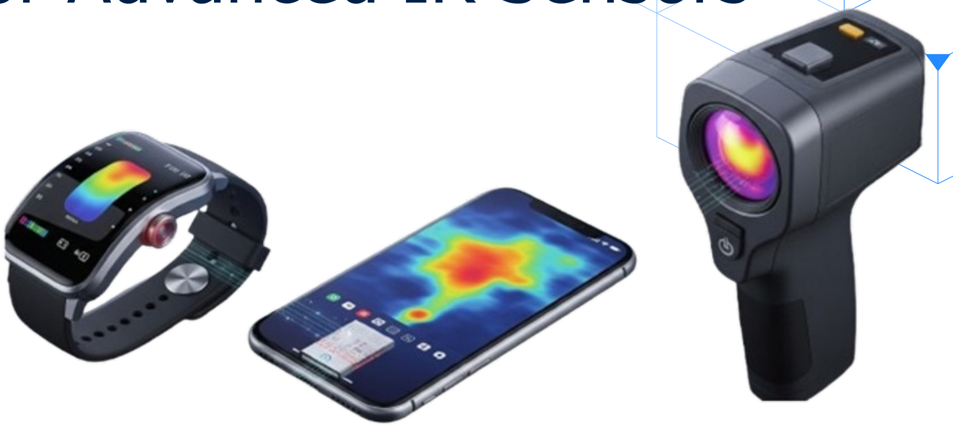
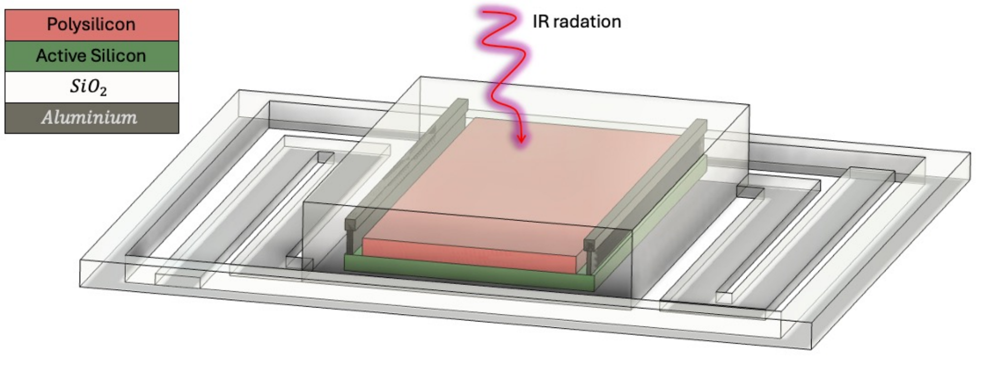
Agenda

Introduction- The Growing Need for Advanced IR Sensors

- **Problem:** Increasing demand for compact, low-power infrared (IR) sensors in wearables, mobile devices, IoT, and thermal imagers faces challenges with size, power, and semiconductor integration.
- **Solution:** Thermal Metal-Oxide-Semiconductor (TMOS) technology offers high sensitivity, low power, and CMOS compatibility.
- **Further Enhancement:** Optimizing spectral selectivity and optical efficiency of absorbing layers is crucial for TMOS performance.
- **Challenge with Traditional Filters:** Conventional optical filters are often bulky or incompatible with CMOS fabrication, hindering on-chip spectral selectivity





TMOS schematic
3D cross-section

Introduction- TMOS Sensor Technology Fundamentals

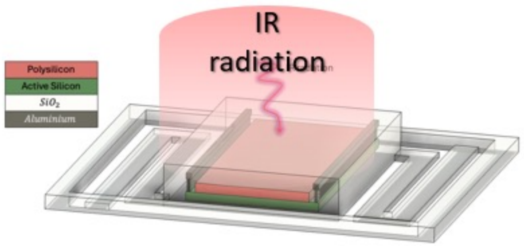
CMOS-SOI-MEMS Technology: Advances in this technology have driven the development of low-cost, compact, and efficient IR sensors.

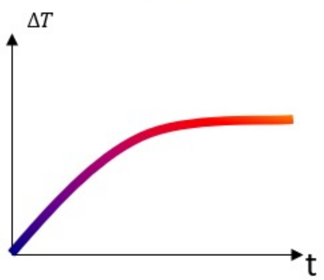
TMOS Sensor Mechanism: Leverages a suspended, micro-machined, thermally insulated transistor to directly convert absorbed IR radiation into an electrical signal.

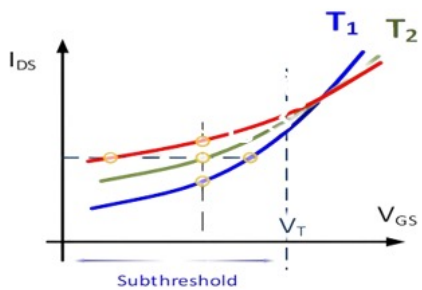
Advantages: Ultra-low power consumption (micro-Watt range) and high temperature sensitivity due to operation in the subthreshold regime.

TMOS operation principle:

1. The transistor absorbs infrared radiation
2. causing a temperature change
3. which converted into an electrical signal

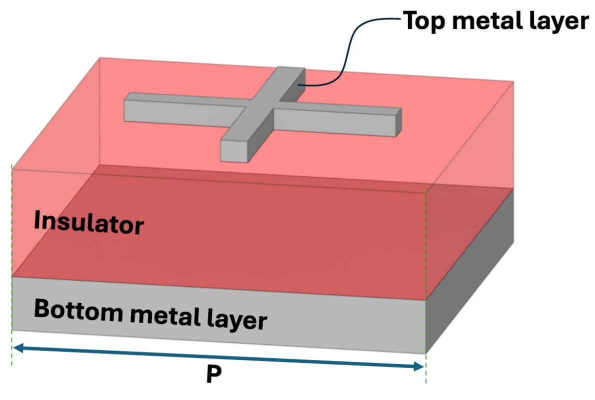


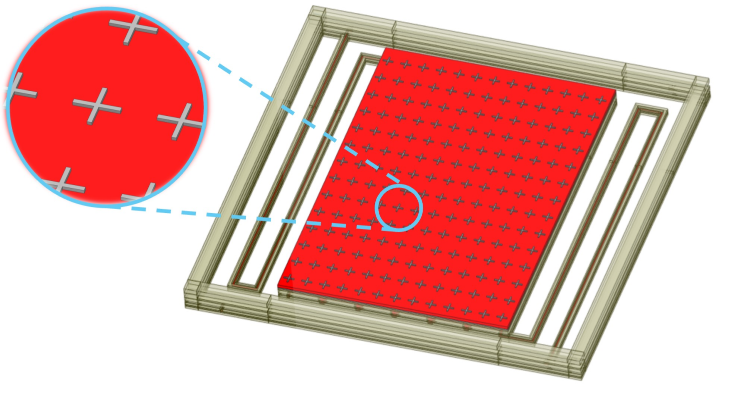




Metal-Insulator-Metal (MIM) Metasurfaces as a Solution

- **Introduction to MIM Metasurfaces:** Subwavelength structures designed for precise optical responses, including strong absorption and spectral filtering, in an ultra-thin, planar configuration.
- **Key Advantage:** Can be monolithically integrated into the same CMOS-SOI layer as the TMOS device, enabling flat optics with minimal cost and footprint.
- **Absorption Mechanism:** The patterned top layer supports localized surface plasmon resonances, which may couple to different resonance type, that concentrate the electromagnetic field within the dielectric, leading to high absorption and spectral filtering.
- **Design Complexity:** Designing MIM structures for specific spectral requirements, especially in the Long-Wave Infrared (LWIR) region, can be challenging.





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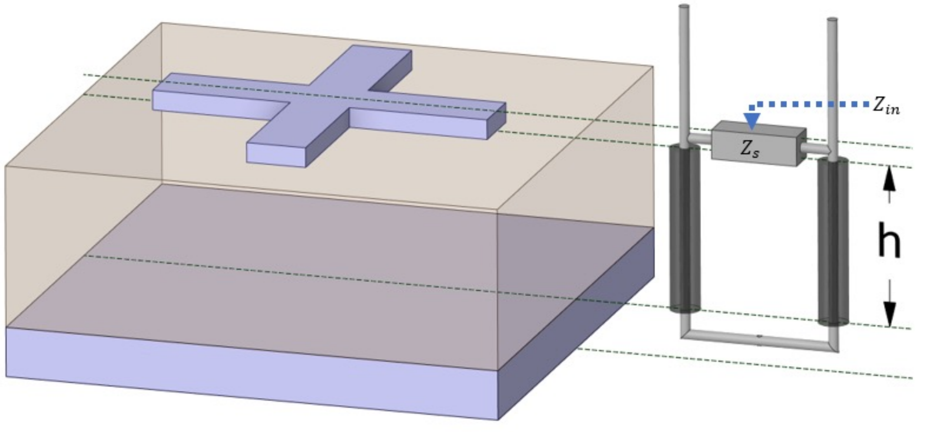
Overcoming Design Challenges: Intuition with Equivalent-Circuit Models

- **Full-Wave Simulations:** Computationally intensive and offer limited intuitive guidance for the design process
- **Equivalent-Circuit Models:** Simplify complex electromagnetic interactions into an electrical circuit, providing intuitive understanding of design parameters and significantly reducing simulation time.
- **Paper's Focus:** Presents a methodology (geometry and material selection) for designing MIM absorbers in the mid-infrared and LWIR regions using equivalent circuit modeling

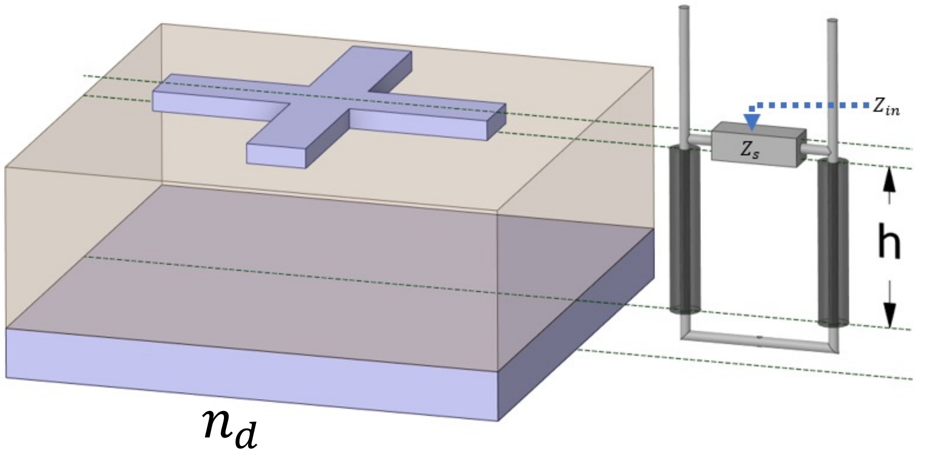


Perfect Absorption and Transmission Line Circuit Model

- **Modeling Approach:** The MIM absorber's electromagnetic behavior can be analyzed using a transmission line circuit model.
- **Model Components:**
  - Surface impedance: Z_s
  - Transmission line stub (dielectric spacer)
  - Ground plane
- Transmission line equation:

$$Z_{in} = \frac{jZ_s Z_d \tan(\beta h)}{Z_s + jZ_d \tan(\beta h)} \Rightarrow Z_s = \frac{jZ_{in} Z_d \tan(\beta h)}{jZ_d \tan(\beta h) - Z_{in}}$$

$$\text{where: } Z_d = Z_0/n_d,\ \beta = 2\pi n_d/\lambda_0,$$
$$Z_0 = 377\ (free\ space\ impedance)$$



- **Perfect Absorption:**
  - At resonance $tan(\beta h) \gg Z_s$
  - $Z_s \approx Z_{in}$
  - $\mathrm{R} = \Gamma^2 = \left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right|^2 \approx 0$
  - Since there is no transmission through bottom layer → perfect absorption achieved

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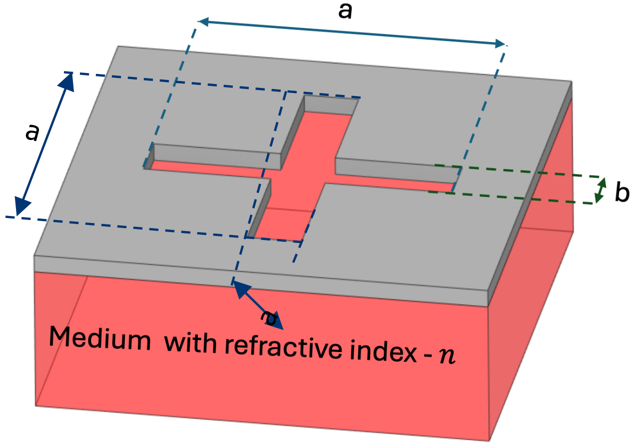
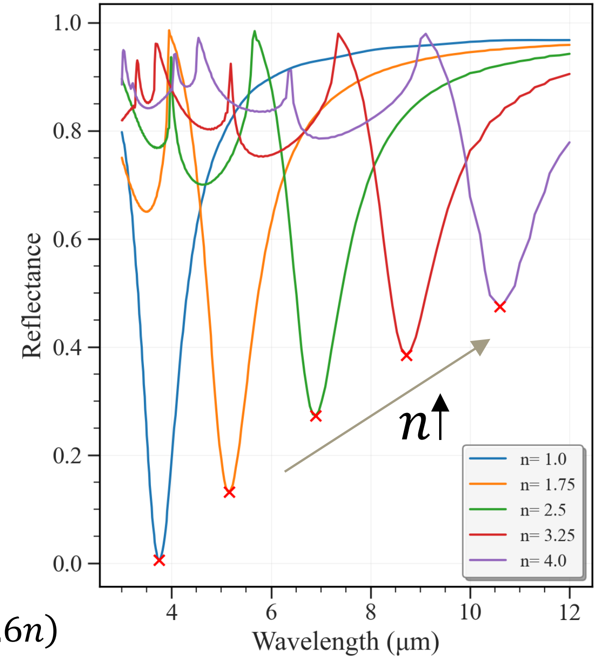
Absorber Design Methodology

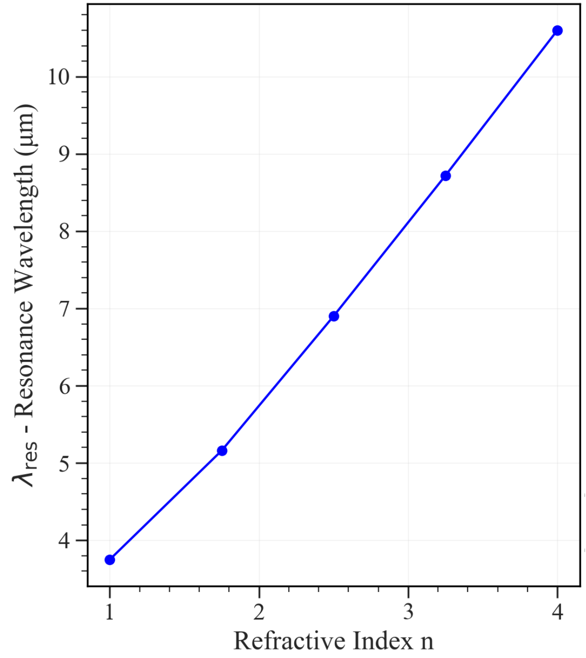
- **Resonance Wavelength Tuning:** Primarily determined by
  - the dipole length
  - and dielectric refractive index

$$\lambda_{res} = 2n_{eff}a$$



- For the tuned wavelength resonance, **Perfect absorption** mainly determined by:
  - The dielectric thickness
  - The dipole width (b)





$$\lambda_{res} = \lambda_{res_0} \times \underbrace{(0.4n_{air} + 0.6n)}_{n_{eff}}$$

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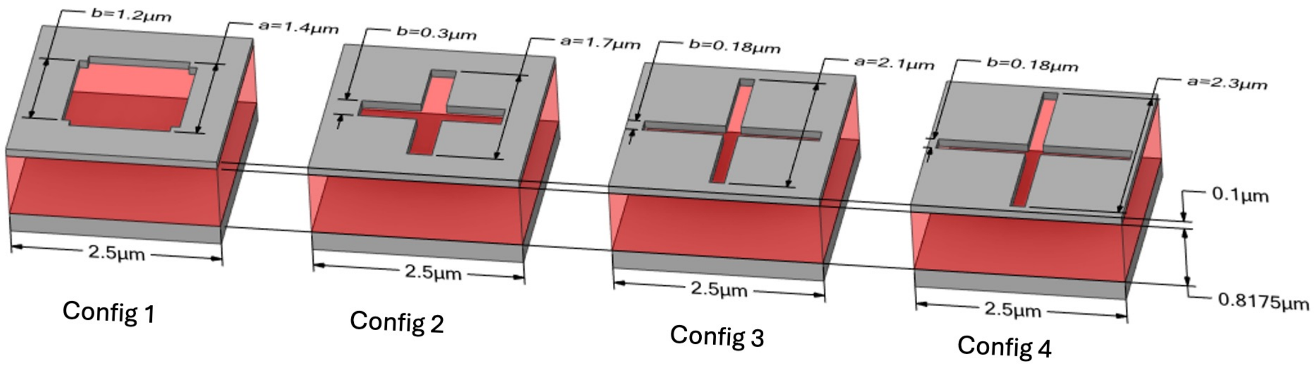
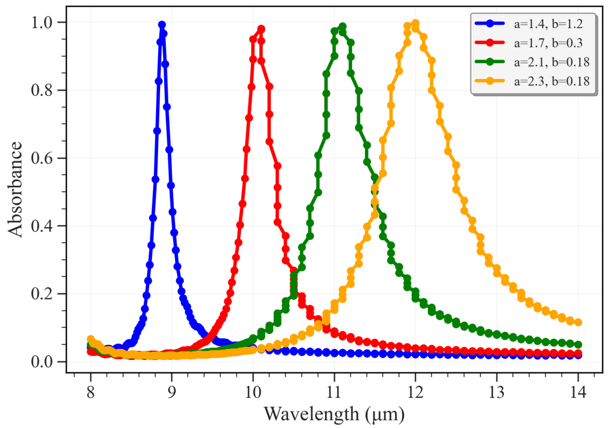
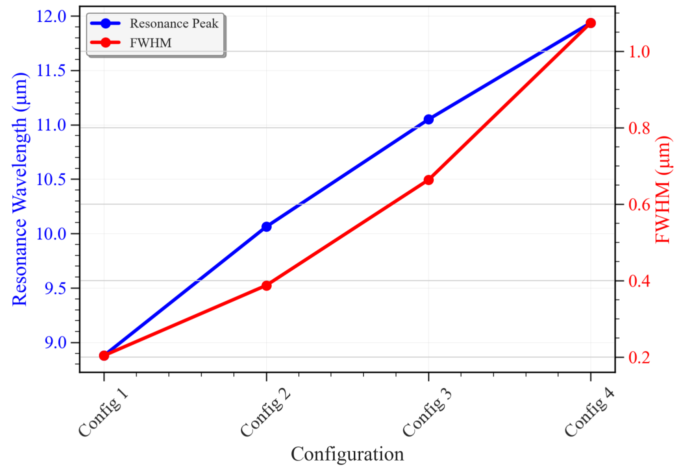
Optimized Designs and Spectral Response

- Several MIM meta-absorber structures with a bottom reflector metal layer were tested and simulated.
- **Performance:** All optimized designs exhibit near-perfect absorption (exceeding 95%) in the LWIR range (8-14 microns)
- **Tunability:** A clear redshift in resonance wavelength is observed as geometric parameters (arm length 'a' and arm width 'b') of the top metallic pattern are varied.





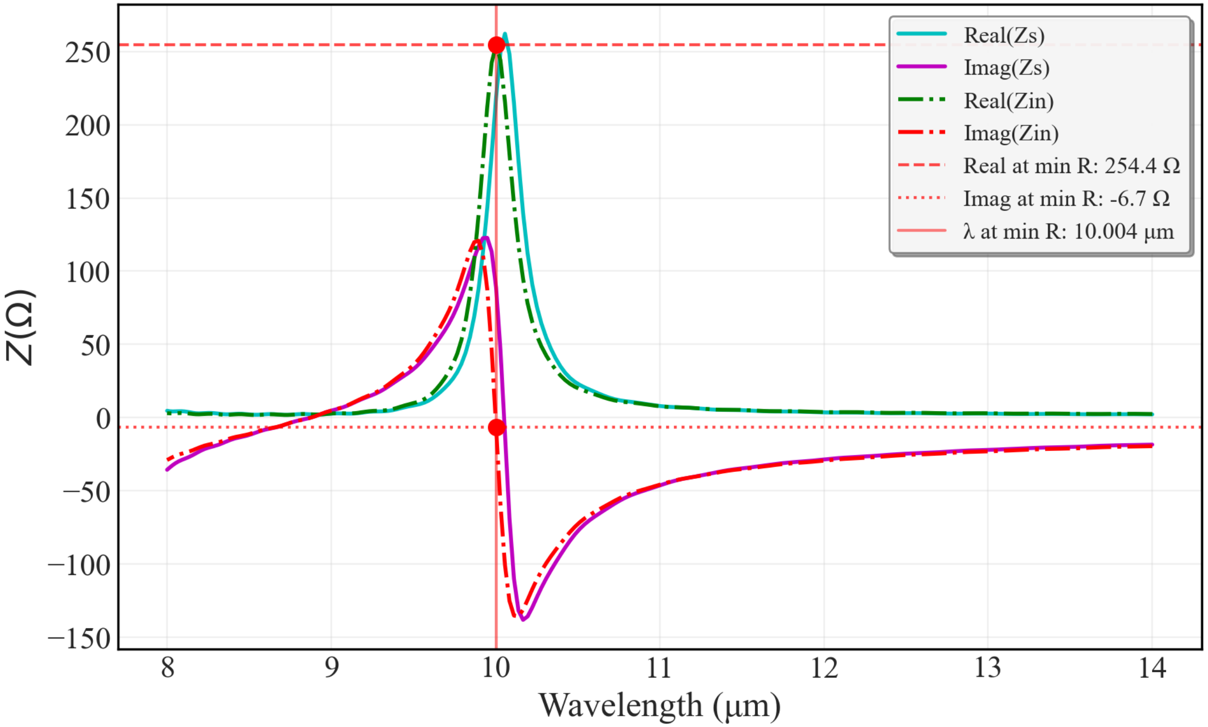


Understanding the Surface Impedance (Zs)

- **Importance of Zs:** Crucial for understanding the individual contributions of the patterned metallic layer to the absorption mechanism and validating the transmission line model.

- **Resistive Loss:** The peak in the real part of Zs at the resonance wavelength indicates maximum resistive loss, essential for efficient absorption.

- **Impedance Matching:** The plots for Zs show how the patterned layer's impedance contributes to achieving the critical impedance matching condition at different resonance wavelengths.



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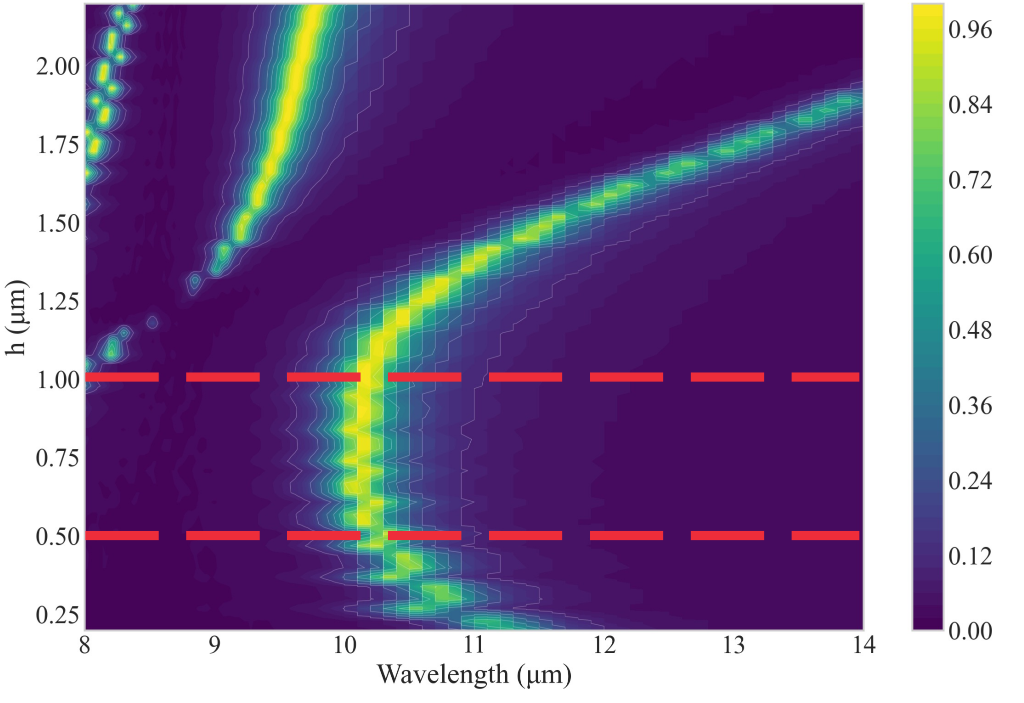
Impact of Dielectric Spacer Layer Thickness

- **Crucial Role:** The thickness of the dielectric spacer layer (h) plays an equally crucial role in tuning absorption characteristics and achieving impedance matching.

- **Effect on Resonance:** Varying dielectric thickness significantly impacts both the resonance wavelength and overall absorption efficiency.

- **Optimal Performance:** Contour plot illustrates how specific combinations of wavelength and dielectric thickness lead to minimal reflectance (high absorption), highlighting the importance of precise control during fabrication.

- For relatively thick dielectric spacer ($0.5 < h < 1\mu m$) at resonance $\boldsymbol{Z_s} \ll \boldsymbol{Z_{dielectric}}$ which leads to $Z_{in} \approx Z_s$



Discussion and Key Findings

- **Equivalent-Circuit Model Efficacy:** Proved to be a useful tool, offering significant physical insight, reducing computational burden (less parameters for the grid search)
- **Dielectric Substrate's Role:** Critical role of the dielectric substrate's refractive index in determining spectral response and tunability
- **Geometric Engineering:** Precise control over absorption characteristics achieved by modifying geometric parameters of top metallic patterns, leading to spectral shifts and maintaining narrow FWHM values
- **Redshift and FWHM Trade-off**: Red shifting the resonance wavelength often leads to a larger FWHM due to increased physical dimensions and potential for increased losses

Conclusions and Future Outlook

- **Summary of Achievements:**
  - Methodology for designing high-performance MIM metamaterial absorbers for LWIR applications presented
  - Validated by full-wave simulations (FDTD – Lumerical)
  - Silicon is identified as optimal dielectric, enabling compact geometries and spectrally selective responses
  - Precise control over absorption wavelength and spectral selectivity is achieved through metallic pattern engineering, yielding near-unity absorption
  - Transmission-line circuit model provided valuable physical insight into impedance-matching conditions

- **Future Impact:** Paves the way for monolithic integration of spectrally selective optical filters directly onto CMOS–SOI–MEMS TMOS sensors

- **Enabling:** Miniaturized, cost-effective, and functionally enhanced next-generation infrared sensing systems

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Thank You for Your Attention!

Questions?