# Advancing Sensing Capabilities: Hybrid Integration of Orthogonal Mode Couplers with Plasmonic Waveguides

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**Abstract:** In this work, a plasmonic sensor based on metal–insulator–metal (MIM) waveguide for temperature sensing application is numerically investigated via finite element method (FEM). The resonant cavity filled with PDMS polymer is side-coupled to the MIM bus waveguide. The sensitivity of the proposed device is ~ − 0.44 nm/°C which can be further enhanced to − 0.63 nm/°C by embedding a period array of metallic nanoblocks in the center of the cavity. Orthogonal mode couplers are designed for plasmonic chips, which leverage MIM waveguide-based sensors. The optimized transmission of the hybrid system including silicon couplers and MIM waveguide is in the range of − 1.73 dB to − 2.93 dB for a broad wavelength range of 1450–1650 nm.

**Sensor design:** The design includes a circular cavity filled with a PDMS layer, side-coupled with an MIM bus waveguide (Figure 1(a))[1]. PDMS is ideal for temperature sensing because it responds well to temperature changes, making it a highly sensitive material for detecting fluctuations. The refractive index of PDMS exhibits variations in response to temperature changes due to the inherent thermal expansion properties of the material. The optimized sensor design was tested across a temperature range of 20 to 80 °C. The refractive index of PDMS shows a linear relationship with temperature as shown in Figure 1 (b). The sensitivity of the device is numerically estimated at -0.44 nm/°C.

Figure 2 show the normalized H-field distribution in the sensor at wavelengths of 1549.4 nm (on-resonance) and 1516.5 nm (off-resonance). In the on-resonance state (Figure 2 (a)), light from the silicon input waveguide is coupled into the MIM waveguide as SP wave modes and then into the cavity. In the off-resonance state (Figure 2 (b)), the light stays in the MIM waveguide and transforms back into a dielectric mode, which is collected by the silicon waveguide [1].

**Sensitivity enhancement mechanism:** The system enhances sensitivity by adding an 8×8 array of 50 nm² metallic nanoblocks, spaced 25 nm apart, to a circular cavity (Figure 3 (a)). This confines the electric field near the blocks, improving responsiveness to temperature-induced refractive index changes in the PDMS layer. In Figure 3 (b), the resonance dip shifts towards higher wavelengths, leading to an analysis between 1900-2100 nm. A blueshift in the resonance wavelength occurs with rising ambient temperature, with a slope of -0.63 nm/°C, indicating a 43% increase in sensitivity due to the metallic nanoblocks (Figure 3 (c)). Sensitivity can be further improved by optimizing the cavity shape. Figures 3 (d, e) show the E-field and H-field distributions, with Figure 3 (d) highlighting intensified E-field confinement along the nanoblock boundaries, enhancing light-matter interaction and overall sensitivity [1].

**Concluding remarks:** Herein, a systematic numerical analysis of a cutting-edge plasmonic sensor designed for temperature sensing applications was conducted, employing a MIM waveguide. The sensor's design features a circular cavity that is filled with a thermo-optic material, specifically PDMS. This cavity is side coupled to a MIM bus waveguide resulting in a ring resonator configuration. The transmission of light into and out of this nanoscale waveguide is efficiently managed through silicon-based orthogonal couplers. These couplers play a fundamental role in seamlessly transforming dielectric modes into plasmonic modes and vice versa. Such transformation capabilities enhance the sensor's performance and ensure optimal functionality. The proposed sensor design offers a sensitivity of − 0.44 nm/°C over a temperature range spanning from 20 to 80 °C which can be further amplified to − 0.63 nm/°C by incorporating a periodic array of metallic nanodots in the center of the cavity. This characteristic makes it an excellent choice for precision temperature measurements. The outcomes of this study represent a significant step towards the growth and deployment of plasmonic sensing devices employing MIM waveguides, with the potential for a wide array of applications beyond temperature sensing.

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**Figure 1.** (**a**) Schematic of a plasmonic chip for temperature sensing, (**b**) Refractive index of PDMS versus ambient temperature [1].

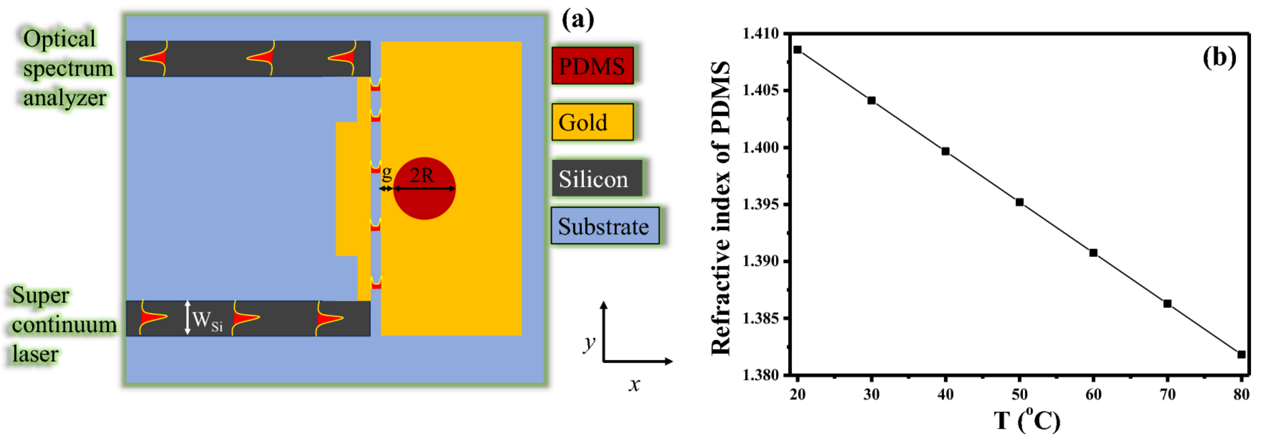


**Figure 2**. Normalized H-field distribution in the sensor at, (**a**) resonant wavelength = 1549.4 nm, (**b**) non-resonant wavelength = 1516.5 nm [1].

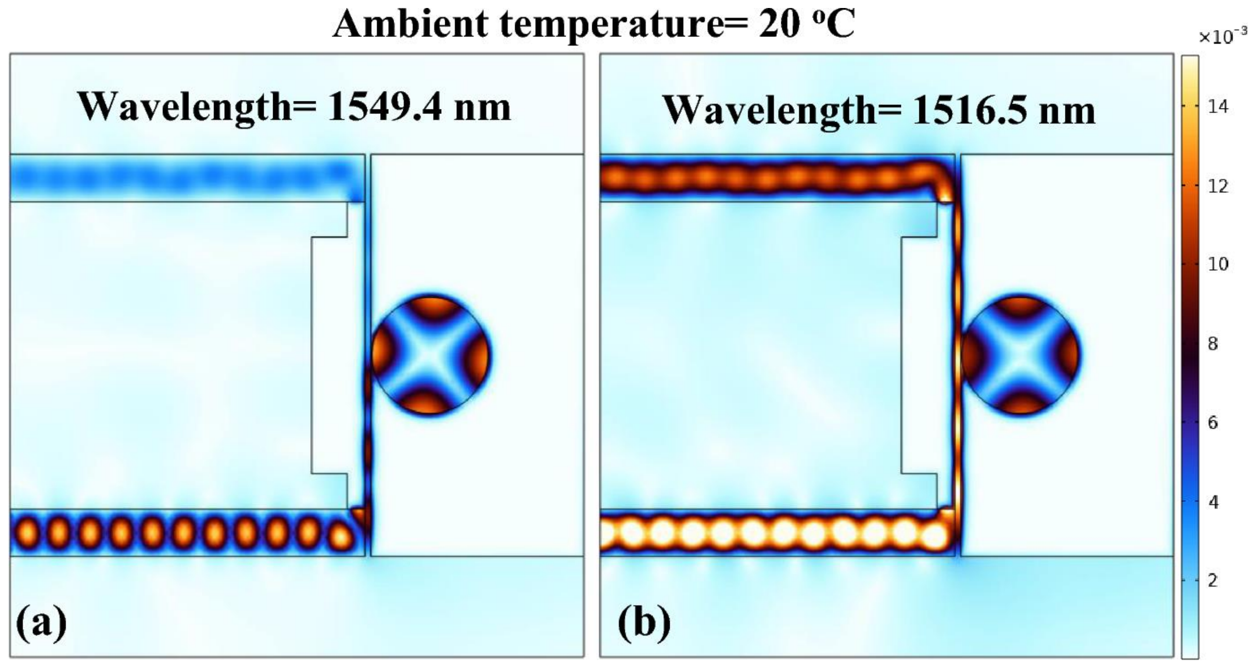
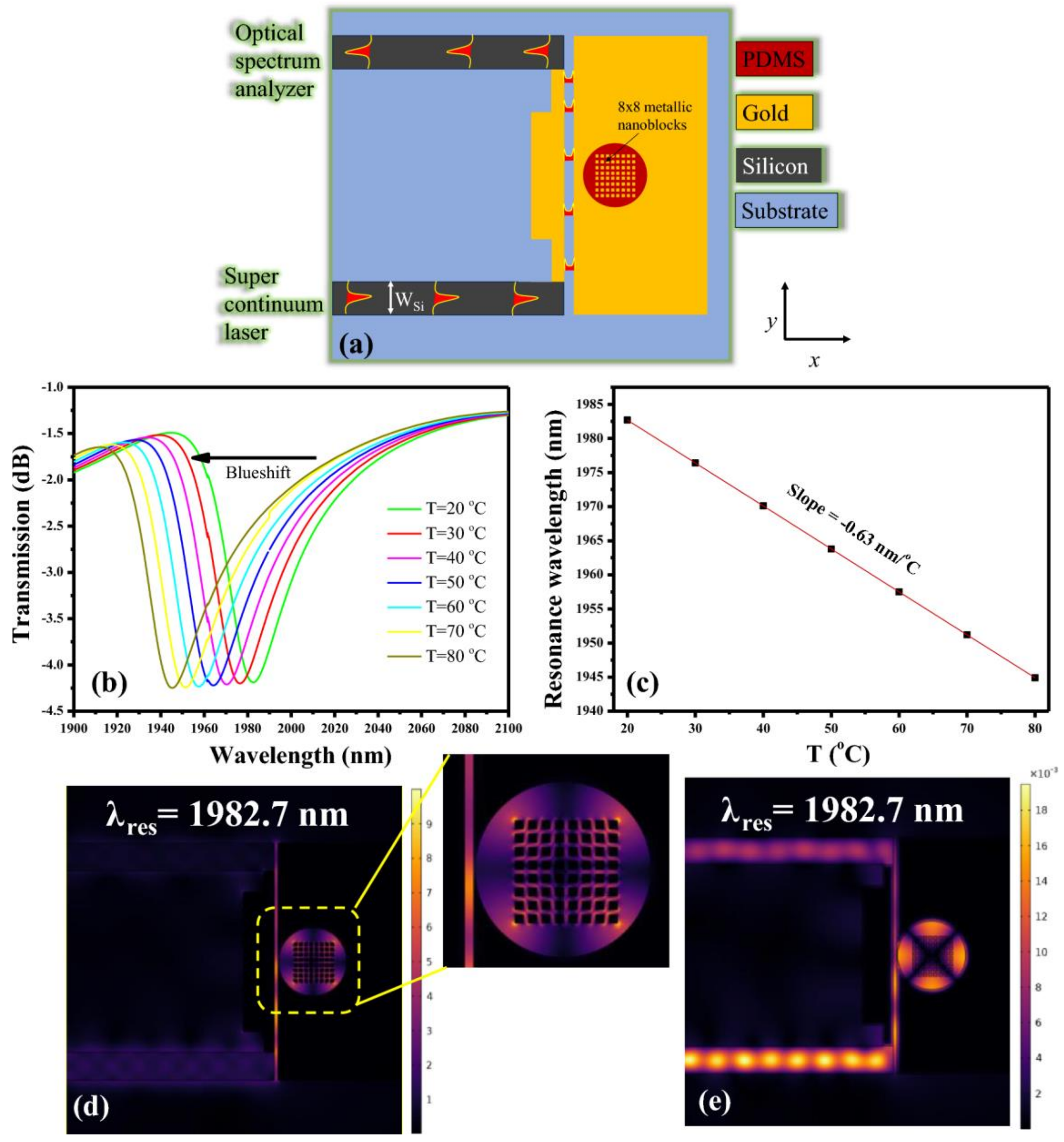


**Figure 3.** (a) Diagram of a plasmonic sensor with metallic nanoblocks in its cavity, (b) Transmission spectrum of the sensor as ambient temperature changes, (c) Resonance wavelength shifts with ambient temperature, (d) Normalized E-field distribution in the sensor at a 1982.7 nm wavelength and 20°C, (e) Normalized H-field distribution in the sensor at the same wavelength and temperature [1].



**Reference**
[1] Butt, M.A., Piramidowicz, R. Orthogonal mode couplers for plasmonic chip based on metal-insulator-metal waveguide for temperature sensing applications. Sci Rep. 14, 3474 (2024).