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Thermally Tunable Refractive-Index Sensing Using Dual-Interface VO_2 in a Metal–Dielectric–Metal Plasmonic Waveguide

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ABSTRACT

We present a thermally tunable metal–dielectric–metal plasmonic waveguide sensor that uses ultrathin VO_2 layers at both metal–dielectric interfaces to enhance refractive-index sensitivity. The proposed sensor has a simple and compact configuration, providing high sensing performance without requiring complex resonant geometries. We analyze the effect of VO_2 position and phase state on the transmission response and compare structures without VO_2, with VO_2 at a single interface, and with VO_2 at both interfaces. The sensing response is evaluated at 30 and 80 °C, corresponding to the insulating and metallic states of VO_2, respectively. The results show that locating VO_2 at both interfaces provides higher sensitivity than the single-interface and VO_2-free configurations. We further engineer the VO_2 thickness from 2 to 5 nm and examine its effect on the wavelength shift produced by changes in the sample refractive index. The thickness dependence differs between the two phases, while the metallic state consistently provides a stronger sensing response. The optimized structure with a 5-nm VO_2 layer reaches a maximum sensitivity of 1828 nm/RIU at 80 °C, compared with 1093 nm/RIU at 30 °C. These results show that controlling the VO_2 interface configuration, phase state, and thickness provides an effective approach for improving the refractive-index response of MDM plasmonic waveguides while maintaining a simple and compact structure.

Introduction

Plasmonic waveguides provide a compact platform for refractive-index sensing because they confine electromagnetic (EM) fields near metal–dielectric interfaces[1]. The strong interaction between the plasmonic field and the surrounding medium makes the optical response sensitive to changes in refractive index (RI)[2–5]. In wavelength-based sensing, this response appears as a shift in the position of transmission peaks or dips when the RI of the sample changes. The sensing performance therefore depends on the field confinement, material properties and interaction between the guided plasmonic mode and the sensing region[6].

Metal–dielectric–metal (MDM) waveguides provide a simple geometry for controlling plasmonic propagation at the nanoscale. The dielectric region between metallic layers confines the EM field and supports strong interaction with the surrounding medium. MIM/MDM structures have therefore been widely studied for RI sensing, where changes in the sample RI produce measurable spectral shifts[7–9]. The coupling between a waveguide and a resonant region can further modify the transmission response and increase the interaction between the optical field and the sensing medium[8,9]. At the same time, increasing structural complexity is not always necessary for obtaining a strong sensing response. This makes simple waveguide configurations attractive for developing compact plasmonic sensors.

The optical properties of the materials located near the plasmonic interface also play an important role in determining the sensor response. Graphene and other dispersive materials have been used to control the EM field and tune the optical response of plasmonic structures[10–12]. Previous studies have shown that material selection and interface engineering can affect the propagation and sensing characteristics of plasmonic waveguides[10–12]. These results indicate that controlling the optical properties close to the metal–dielectric interface can provide an effective way to modify the sensing response. However, materials with fixed optical properties provide limited control once the structure is fabricated. A phase-change material can offer an additional degree of control because its optical properties can change in response to temperature.

Vanadium dioxide (VO_2) is a well-known phase-change material with strong temperature-dependent optical properties. Near its transition temperature, VO_2 changes from an insulating state to a metallic state, accompanied by significant changes in its electrical conductivity, RI and optical absorption[13–15]. The transition occurs near 68 °C and can be reversed when the temperature decreases[14,15]. These properties make VO_2 useful for thermally tunable optical and plasmonic structures. In particular, the change in the complex RI of VO_2 can alter the EM field distribution and optical loss near a metal–dielectric interface, providing a direct mechanism for controlling a plasmonic response.

Several studies have used VO_2 to control optical and plasmonic responses through its phase transition[15–17]. These studies demonstrate that the transition of VO_2 can modify resonance characteristics, transmission and other optical properties. However, the integration of an ultrathin VO_2 layer directly at the metal–dielectric interface of a simple MDM waveguide provides a different approach to RI sensing. In particular, the effect of the number of VO_2-containing interfaces, the phase state of VO_2, and the VO_2 thickness on the wavelength sensitivity has not been systematically examined in a single compact MDM configuration. This gap is important because the position and thickness of the phase-change layer directly determine its interaction with the confined plasmonic field.

In this work, we present a simple and compact MDM plasmonic waveguide sensor that uses ultrathin VO_2 layers at the metal–dielectric interfaces. We first analyze the optical properties of VO_2 at 30 and 80 °C and compare the sensing response of structures without VO_2, with VO_2 at a single interface, and with VO_2 at both interfaces. We then analyze the wavelength shift produced by sample RIs from 1.33 to 1.40 and determine the corresponding sensitivity. After selecting the dual-interface configuration, we engineer the VO_2 thickness from 2 to 5 nm and examine its effect on the sensing response at both temperatures. The results show that the dual-interface configuration provides a higher sensitivity than the other configurations and that the metallic phase of VO_2 produces a stronger wavelength response. The optimized structure reaches a maximum sensitivity of 1828 nm/RIU at 80 °C for a 5-nm VO_2 layer. The results show that controlling the interface position, phase state, and thickness of ultrathin VO_2 provides an effective way to enhance the RI response while maintaining a simple plasmonic geometry.

Our article is organized as follows. The Model section describes the proposed structure and its theoretical formulation, followed by the Results and Discussion sections, which present and interpret the obtained results. The Methods section describes the FEM procedure and the simulation conditions.

Model

Figure 1 shows the schematic configuration of the proposed MDM plasmonic sensor. The structure consists of two silver (Ag) layers surrounding an air core and forming a planar MDM waveguide. The air core acts as the sensing region, where samples with different RIs are considered. The simple planar configuration provides strong EM field confinement within the air core and allows the confined plasmonic field to interact with the sensing medium.

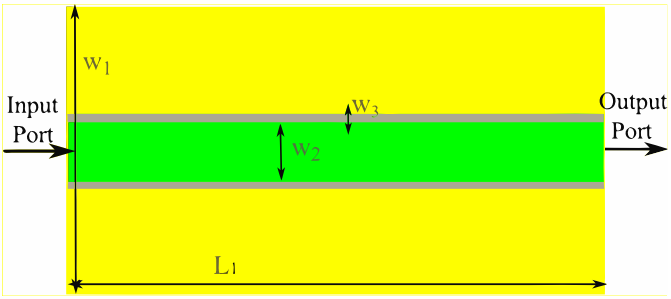


Figure 1. Schematic configuration of the proposed MDM plasmonic sensor. The yellow regions represent the silver (Ag) cladding layers, the green region represents the dielectric core and the gray layers at the metal–dielectric interfaces represent the VO_2 layers.

The geometrical parameters of the proposed structure are set as $W_1 = 400$ nm, $W_2 = 50$ nm, $W_3 = 20$ nm, and $L_1 = 600$ nm.

Silver is used as the metallic cladding of the MDM waveguide. The frequency-dependent dielectric response of silver is described using the Drude model[12]. The relative permittivity of the metal is expressed as

$$\frac{\varepsilon_{\mathrm{Ag}}(\omega)}{\varepsilon_0} = \varepsilon_{\mathrm{b}} + \frac{F\omega_{\mathrm{e}}^2}{\omega_0^2 - \omega^2 + i\Gamma_{\mathrm{e}}\omega}, \tag{1}$$

where ε_{b} is the background dielectric constant, F is the oscillator strength, ω_0 is the resonance frequency, ω_{e} is the electric plasma frequency, Γ_{e} is the electric damping constant, and ω is the angular frequency. For silver, the parameters are set to $F = 1$, $\omega_0 = 0$, $\omega_{\mathrm{e}} = 1.37 \times 10^{16}$ s^{-1}, and $\Gamma_{\mathrm{e}} = 2.73 \times 10^{13}$ s^{-1}, following our previous plasmonic sensor model[12]. The permeability of silver is considered constant and equal to $\mu = 1$.

Ultrathin vanadium dioxide (VO_2) layers are located at the metal–dielectric interfaces of the MDM waveguide. The initial thickness of each VO_2 layer is 2 nm, as shown in Figure 1. Locating VO_2 at the metal–dielectric interfaces allows its temperature-dependent optical response to interact directly with the confined plasmonic field. Two configurations are considered to analyze the effect of the VO_2 position: VO_2 at one metal–dielectric interface and VO_2 at both interfaces.

The optical properties of VO_2 are strongly temperature dependent and change significantly across the dielectric–metal transition. In this work, wavelength-dependent complex RI data for VO_2 at 30 and 80 °C are obtained from the reported optical data of Oguntoye et al.[18], corresponding to the insulating and metallic states, respectively. The real and imaginary parts of the RI are used to describe the complex optical response of VO_2 over the wavelength range considered in the simulations. These temperature-dependent optical properties are then used as the material input for the VO_2 layers in the numerical model.

The temperature-dependent response of VO_2 is considered at 30 and 80 °C. For each temperature, the corresponding optical properties of VO_2 are used to calculate the transmission response of the proposed structure. The sensing core is then filled with samples having RIs ranging from 1.33 to 1.40. The transmission spectra is calculated for each RI value and the wavelength position of the selected transmission peak or dip is recorded. The resulting wavelength shifts are used to evaluate the RI sensitivity of the sensor.

The RI sensitivity of the proposed sensor is calculated as

$$S = \frac{\Delta\lambda}{\Delta n}, \tag{2}$$

where S represents the RI sensitivity in nm/RIU, $\Delta\lambda$ is the resonance wavelength shift, and Δn is the corresponding change in the RI of the sensing medium.

1 Physical Mechanism of the Sensing Response

The sensing response of the proposed structure originates from the dependence of the guided plasmonic mode on the optical properties of the metal–dielectric interfaces. In the MDM waveguide, the dielectric core is confined between two metallic claddings, and the propagation characteristics of the guided mode are determined by the EM boundary conditions at these interfaces. Because the mode is associated with the metal–dielectric boundaries, a change in the RI of the sensing medium changes the permittivity distribution experienced by the mode. This change modifies its effective propagation constant and, consequently, the spectral condition at which the transmission resonance occurs. The RI-dependent displacement of the resonance wavelength therefore provides the physical basis of the sensing mechanism.

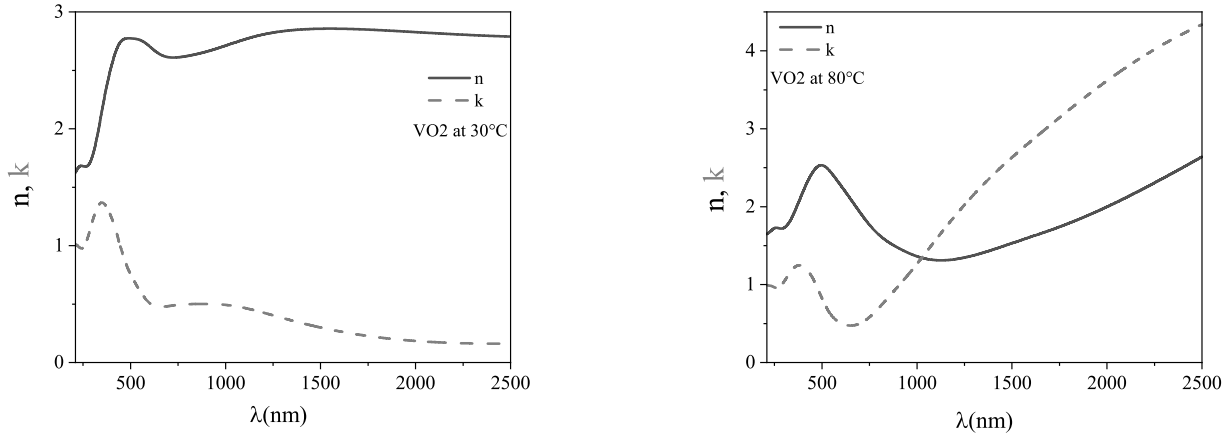
The introduction of an ultrathin VO_2 layer at the metal–dielectric interface changes the local optical environment in which the plasmonic mode propagates. In contrast to the sensing medium, whose RI is varied to generate the sensing signal, VO_2 provides a controllable optical contribution through its complex, temperature-dependent permittivity. The real part of its permittivity affects the phase propagation of the mode, whereas the imaginary part contributes to optical loss and therefore affects the spectral characteristics of the guided response. Consequently, changing the complex optical properties of VO_2 changes the modal propagation and the resonance condition of the MDM structure. The sensing response is thus determined by the combined effect of the sample RI and the optical response of the VO_2-modified interfaces.

The use of VO_2 at both metal–dielectric interfaces further changes the symmetry of the optical environment experienced by the guided mode compared with the single-interface configuration. In the dual-interface structure, both boundaries of the sensing core contain the phase-change material, so the temperature-dependent permittivity of VO_2 contributes to the optical response at both interfaces. A change in the sample RI then acts on a plasmonic mode whose interface conditions are simultaneously controlled by the optical state of VO_2. This provides a physical basis for the different wavelength responses observed for the single- and dual-interface configurations.

The temperature dependence of VO_2 provides an additional control parameter because its insulator-to-metal transition produces a substantial change in its complex optical properties. At 30 °C, VO_2 is considered in its insulating state, whereas at 80 °C it is considered in its metallic state. The associated change in complex permittivity modifies the EM boundary conditions at the interfaces and changes the propagation characteristics of the guided mode. Therefore, for the same variation in the RI of the sensing medium, the resulting resonance displacement can differ between the two temperature states. The higher sensitivity obtained in the metallic state is consequently related to the different optical response of VO_2 and its effect on the plasmonic mode.

The thickness of VO_2 provides another parameter that controls the contribution of the phase-change material to the interface response. Increasing the thickness changes the amount of VO_2 participating in the EM environment of the guided mode and therefore changes the effective optical response of the interface region. This effect is not expected to be identical in the insulating and metallic states because the complex permittivity of VO_2 changes with temperature. The observed thickness dependence of the sensitivity can therefore be understood as a result of the coupled effects of the VO_2 optical state and its geometrical thickness.

From this physical picture, the sensing response of the proposed structure is governed by three coupled parameters: the number of interfaces containing VO_2, the phase state of VO_2, and its thickness. The sample RI determines the perturbation of the optical environment, while the VO_2 layers determine the interface optical conditions under which this perturbation is



(a) 30 °C **(b)** 80 °C

Figure 2. Real (n) and imaginary (k) parts of the RI of VO_2 as a function of wavelength at (a) 30 °C and (b) 80 °C. The solid black curves represent n, while the gray dashed curves represent k.

converted into a spectral shift. The following results examine these effects separately and then determine the configuration that provides the largest RI-induced wavelength response.

Results

Optical Properties of VO_2

The optical response of VO_2 is evaluated at 30 °C and 80 °C, corresponding to its insulating and metallic states, respectively. The real (n) and imaginary (k) parts of the RI are obtained over the wavelength range of 400–2500 nm. Figure 2 shows the wavelength-dependent n and k of VO_2 at the two temperatures.

At 30 °C, the real part n remains relatively high, while the imaginary part k is comparatively small over most of the investigated range. At 80 °C, both components exhibit different spectral behavior compared with the insulating state, with a more pronounced variation in k at shorter wavelengths. These changes in the complex RI of VO_2 affect the EM response of the proposed plasmonic structure.

Baseline Response of the MDM Structure

To establish a reference response for the proposed sensor, the MDM structure is first analyzed without VO_2 layers. In this configuration, the structure consists only of the silver claddings and the dielectric core. The corresponding transmission spectra and the sensitivity of the resonance dips are presented in Fig. 3(a) and (b), respectively.

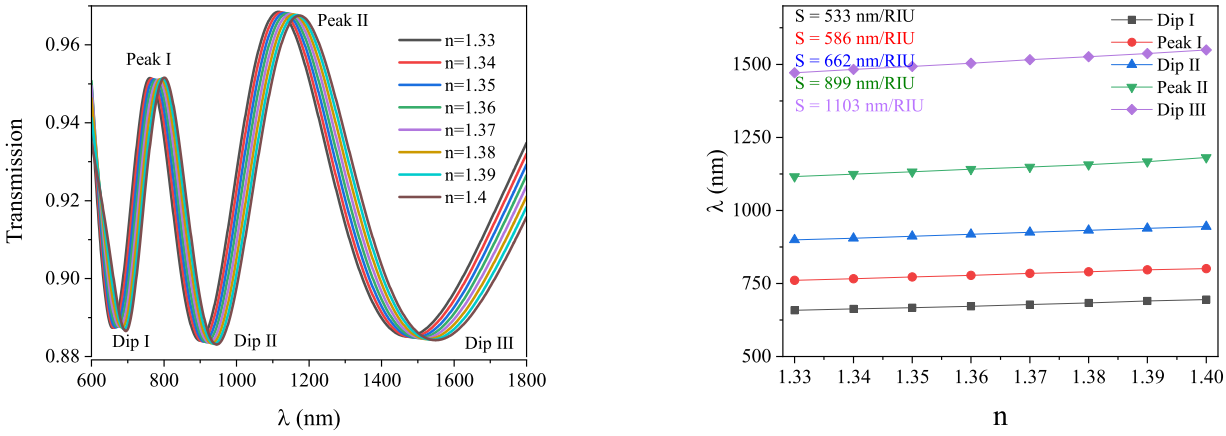
Several distinct resonance dips appear in the transmission spectra, resulting from the interaction of the guided plasmonic modes with the metal–dielectric interfaces of the MDM waveguide. As the RI of the sensing medium increases from 1.33 to 1.40, the resonance dips shift toward longer wavelengths. This shift results from the change in the optical environment of the guided plasmonic modes, which modifies their effective modal properties and consequently the resonance condition.

The sensitivity values obtained from the resonance wavelength shifts are shown in Fig. 3(b). The different resonance dips exhibit different sensitivities, indicating that their interaction with the sensing region is not identical. Among the considered resonances, Dip III shows the largest wavelength shift and provides the highest sensitivity of 1103 nm/RIU. Therefore, Dip III is selected as the reference resonance for the analysis of the VO_2-assisted structures.

MDM Structure with VO_2 at One Interface

To examine the effect of VO_2 on the optical response of the MDM structure, a 2 nm thick VO_2 layer is first located at the upper metal–dielectric interface. The RI of the sensing medium is varied from 1.33 to 1.40, and the transmission response is calculated at 30 °C and 80 °C. The corresponding transmission spectra are shown in Fig. 4.

At 30 °C, several resonance peaks and dips are observed in the transmission spectrum. Increasing the RI from 1.33 to 1.40 shifts the resonance features toward longer wavelengths. The resonance wavelengths are extracted for each RI value, and the corresponding sensitivities are obtained from the wavelength shifts. As shown in Fig. 5, the highest sensitivity is obtained for Peak I, with a value of 693 nm/RIU.



(a) Transmission spectra

(b) Sensitivity of the resonance dips

Figure 3. Response of the MDM structure without VO_2: (a) transmission spectra for different RI values and (b) corresponding sensitivities of the resonance peaks and dips.

The same structure is then evaluated at 80 °C, where VO_2 is in the metallic phase. The corresponding transmission spectra are shown in Fig. 4b. The resonance positions remain sensitive to changes in the RI, while the resonance depths change compared with those obtained at 30 °C. This behavior results from the change in the complex RI of VO_2 between the insulating and metallic phases, which modifies the field distribution and plasmonic mode propagation at the metal–dielectric interface.

For the selected resonance, the wavelength shift is evaluated over the RI range of 1.33–1.40. A linear dependence between the resonance wavelength and RI is obtained, and the corresponding sensitivity reaches 715 nm/RIU. This value is higher than the 693 nm/RIU obtained at 30 °C, indicating that the phase state of VO_2 can modify the RI response of the MDM structure.

The higher sensitivity at 80 °C is associated with the change in the complex optical properties of VO_2, which modifies the plasmonic mode and the resulting resonance response. This change leads to a larger resonance wavelength shift for a given variation in the RI of the sensing medium. Consequently, a given change in RI produces a larger resonance wavelength shift.

The results show that a VO_2 layer at a single metal–dielectric interface provides temperature-dependent control of the resonance response. However, the sensitivity remains lower than that obtained when VO_2 is located at both metal–dielectric interfaces. Therefore, VO_2 is next located at both metal–dielectric interfaces to examine whether the additional interface improves the sensing response.

MDM Structure with VO_2 at Both Interfaces

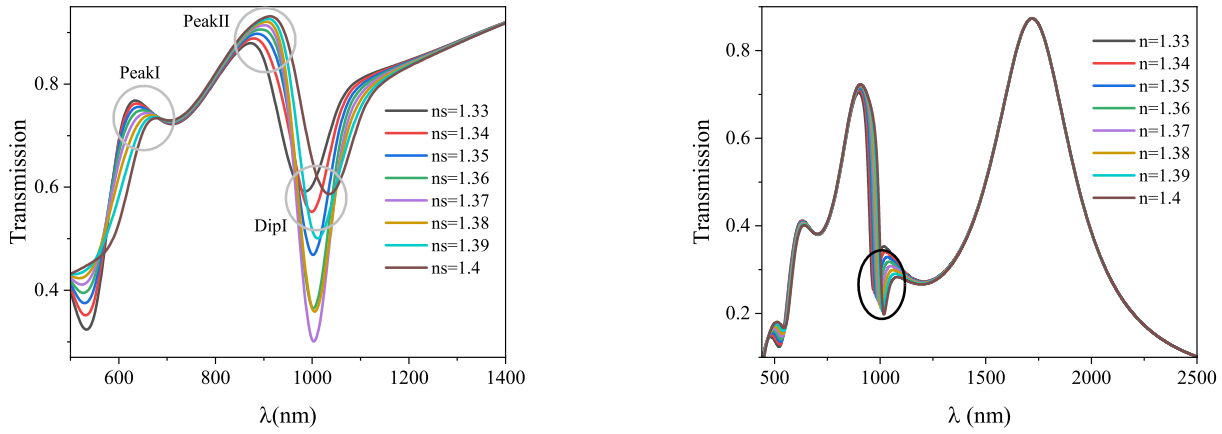
To further examine the effect of the VO_2 position on the plasmonic response, 2 nm thick VO_2 layers are located at both the upper and lower metal–dielectric interfaces of the MDM structure. The sensing medium in the dielectric core is varied over the RI range of 1.33–1.40. The transmission spectra are calculated at 30 °C and 80 °C to evaluate the sensing response in the insulating and metallic states of VO_2.

At 30 °C, several resonance peaks and dips appear in the transmission spectrum, as shown in Fig. 7. The resonance features shift toward longer wavelengths as the RI of the sensing medium increases. This behavior results from the change in the optical environment of the plasmonic modes and their interaction with the sensing region. The presence of VO_2 at both interfaces also changes the optical response of the MDM structure.

The resonance wavelengths are extracted for the considered RI values, and their shifts are analyzed using linear fitting. Figure 8 shows the sensitivity obtained from the identified resonance peaks and dips at 30 °C. Among the analyzed resonances, Dip III exhibits the largest wavelength shift and provides the highest sensitivity of 1090 nm/RIU. The higher sensitivity indicates that this resonance exhibits a larger wavelength response to changes in the RI of the sensing medium.

The same dual-interface structure is then analyzed at 80 °C, where VO_2 is in the metallic phase. The corresponding transmission spectrum is included in Fig. 7(b). Compared with the response at 30 °C, the resonance features show changes in both their spectral contrast and wavelength shift. These changes arise from the temperature-dependent complex RI of VO_2, which changes the plasmonic mode and the resulting interaction with the sensing medium.

The resonance positions are again extracted over the RI range of 1.33–1.40. The resulting wavelength shifts and linear fits are shown in Fig. 9. Peak III exhibits the largest wavelength displacement among the considered resonances. The corresponding



(a) 30 °C **(b)** 80 °C

Figure 4. Transmission spectra of the MDM structure with a 2 nm VO_2 layer located at the upper metal–dielectric interface at (a) 30 °C and (b) 80 °C for different RI values of the sensing medium.

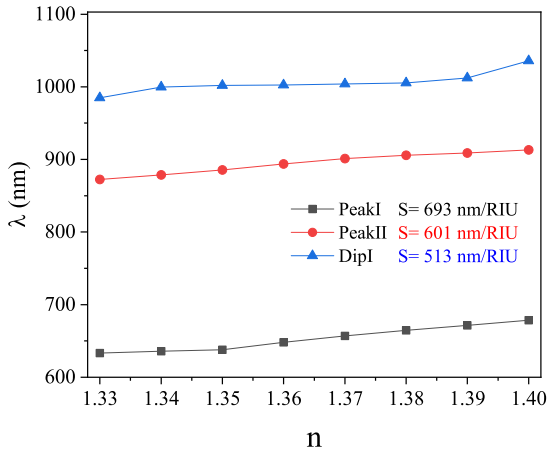


Figure 5. Sensitivity of the resonance peaks and dips for the MDM structure with a 2 nm VO_2 layer at the upper metal–dielectric interface at 30 °C.

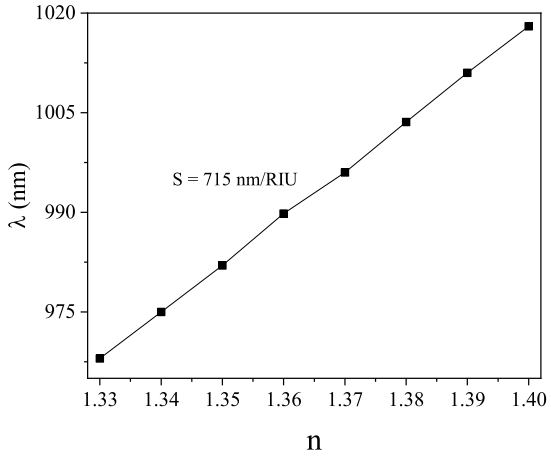
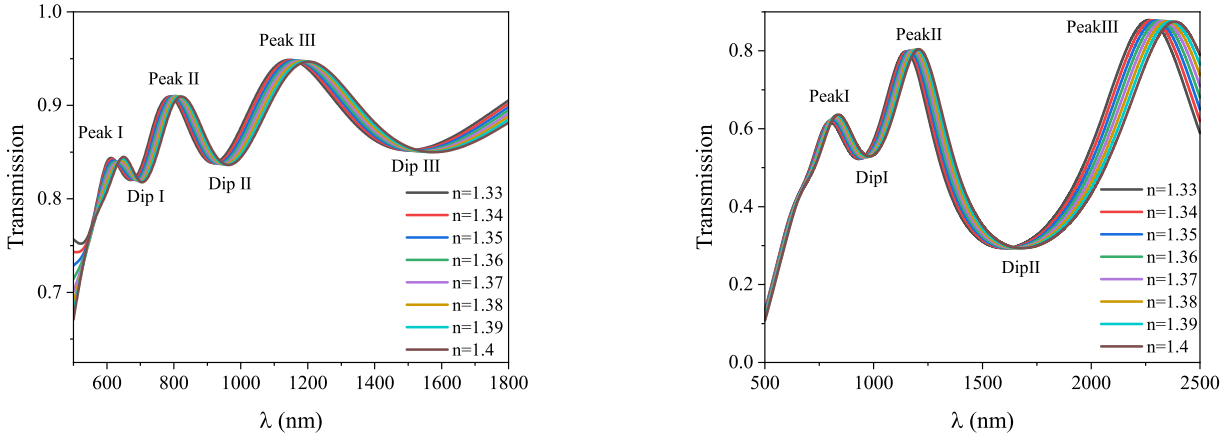


Figure 6. Linear fitting of the selected resonance wavelength as a function of the RI of the sensing medium for the MDM structure with a 2 nm VO_2 layer at the upper metal–dielectric interface at 80 °C.



(a) 30 °C **(b)** 80 °C

Figure 7. Transmission spectra of the MDM structure with 2 nm VO_2 layers located at both metal–dielectric interfaces at (a) 30 °C and (b) 80 °C for different RI values of the sensing medium.

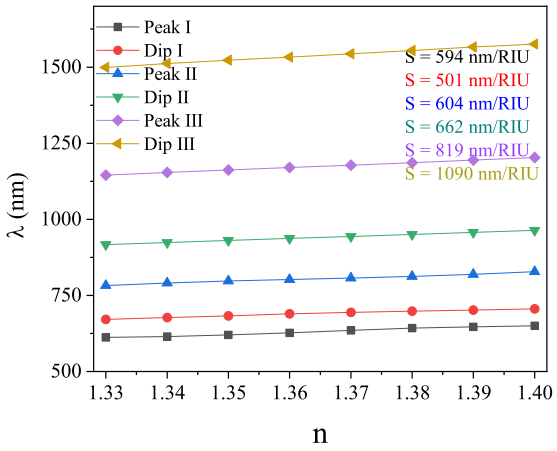


Figure 8. Sensitivity of the resonance peaks and dips for the MDM structure with 2 nm VO_2 layers at both metal–dielectric interfaces at 30 °C.

sensitivity reaches 1699 nm/RIU, which is substantially higher than the 1090 nm/RIU obtained at 30 °C.

The increase in sensitivity at 80 °C indicates that the phase state of VO_2 has a strong effect on the sensing response. The metallic state changes the complex optical properties of VO_2 and modifies the plasmonic mode and the resulting resonance condition. Consequently, the same variation in the RI of the sensing medium produces a larger resonance wavelength shift at 80 °C.

Overall, locating VO_2 at both metal–dielectric interfaces produces a stronger RI-dependent resonance response than the single-interface configuration. The maximum sensitivity increases from 1090 nm/RIU at 30 °C to 1699 nm/RIU at 80 °C. These results show that both the spatial distribution and phase state of VO_2 strongly affect the sensing characteristics of the MDM structure. Therefore, the dual-interface configuration is selected for the optimization of the VO_2 thickness in the following section.

Optimization of VO_2 Thickness

The results presented in the previous section show that locating VO_2 layers at both metal–dielectric interfaces provides a higher sensing response than the single-interface configuration. Therefore, the dual-interface configuration is retained for the geometrical optimization of the sensor. The thickness of the VO_2 layers is selected as the main geometrical parameter and thicknesses of 2, 3, 4, and 5 nm are considered at both metal–dielectric interfaces.

For each thickness, the transmission response is calculated over the considered wavelength range for RI values from 1.33 to 1.40. The resonance wavelength shifts are extracted from the transmission spectra, and the corresponding sensitivities are obtained from the linear variation of the resonance wavelength with RI. The analysis is performed at 30 °C and 80 °C to evaluate the effect of VO_2 thickness in the insulating and metallic states, respectively.

The VO_2 thickness is then increased to 3 nm. Figure 10 shows the transmission responses and sensitivity analyses at the two temperature states. The sensitivity is 1076 nm/RIU at 30 °C and increases to 1732 nm/RIU at 80 °C.

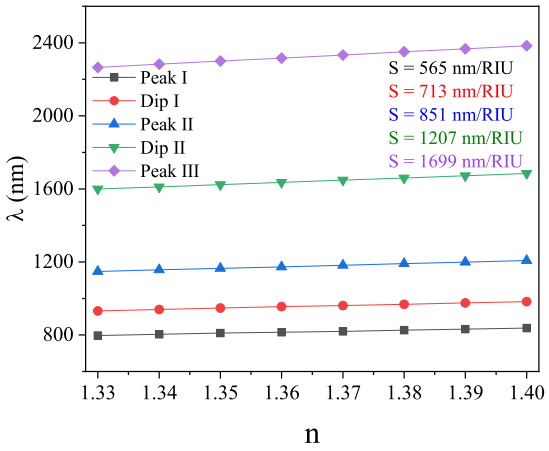
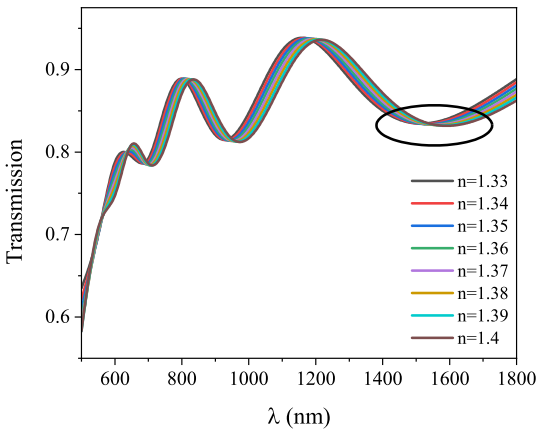
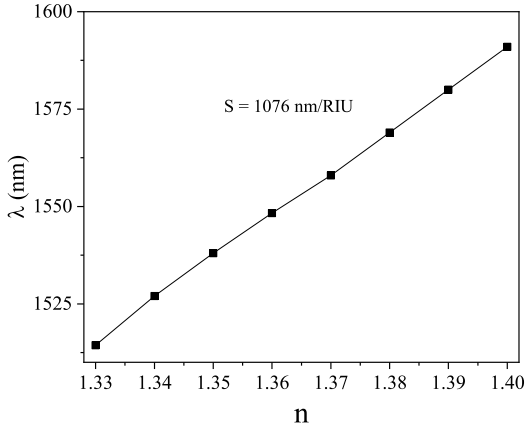


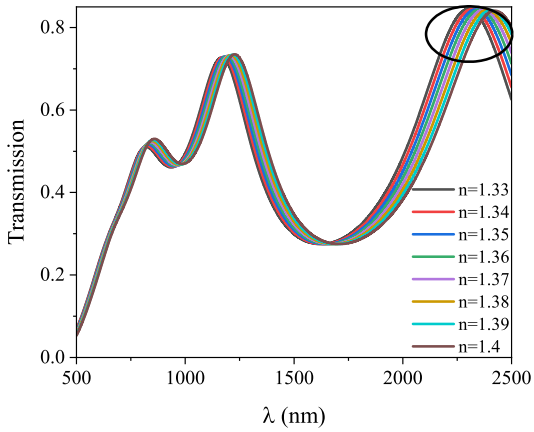
Figure 9. Sensitivity of the resonance peaks and dips for the MDM structure with 2 nm VO_2 layers at both metal–dielectric interfaces at 80 °C.



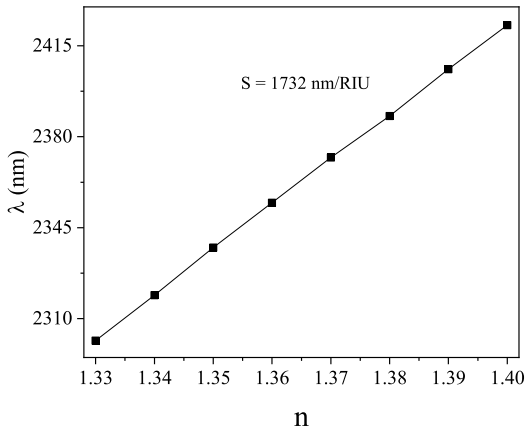
(a) Transmission response at 30 °C.



(b) Sensitivity analysis at 30 °C.



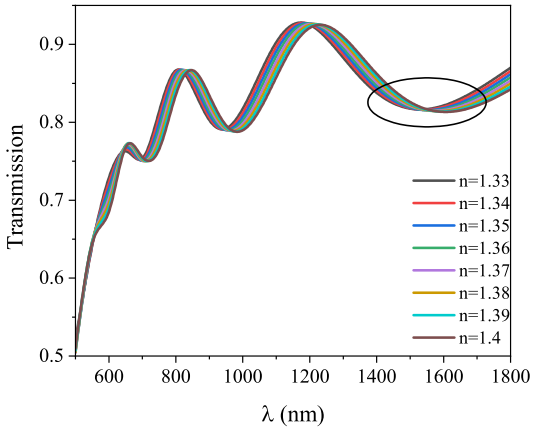
(c) Transmission response at 80 °C.



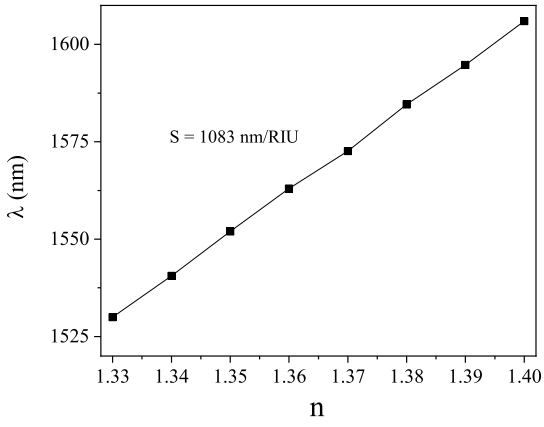
(d) Sensitivity analysis at 80 °C.

Figure 10. Transmission spectra and sensitivity analyses of the dual-interface MDM structure with 3 nm VO_2 layers at 30 °C and 80 °C.

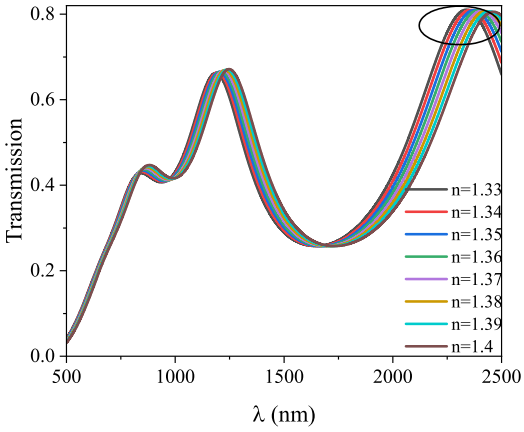
For a VO_2 thickness of 4 nm, the transmission spectra and sensitivity analyses are shown in Fig. 11. The sensitivity is 1083 nm/RIU at 30 °C, whereas it reaches 1750 nm/RIU at 80 °C.



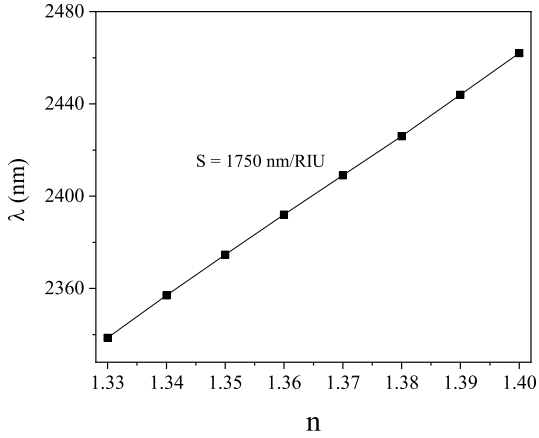
(a) Transmission response at 30 °C.



(b) Sensitivity analysis at 30 °C.



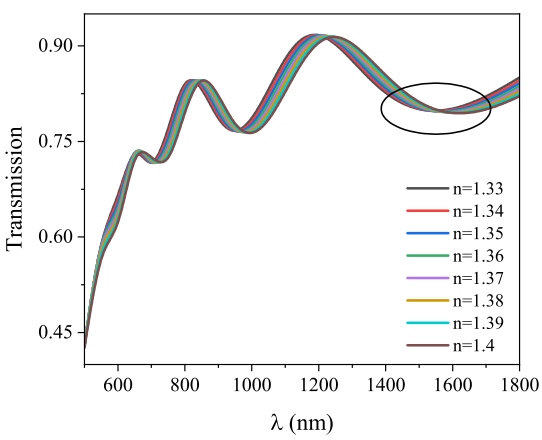
(c) Transmission response at 80 °C.



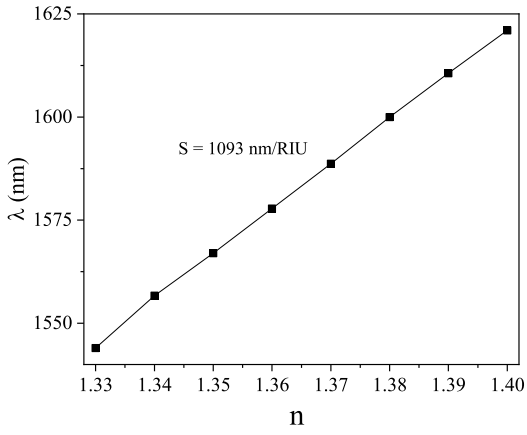
(d) Sensitivity analysis at 80 °C.

Figure 11. Transmission spectra and sensitivity analyses of the dual-interface MDM structure with 4 nm VO_2 layers at 30 °C and 80 °C.

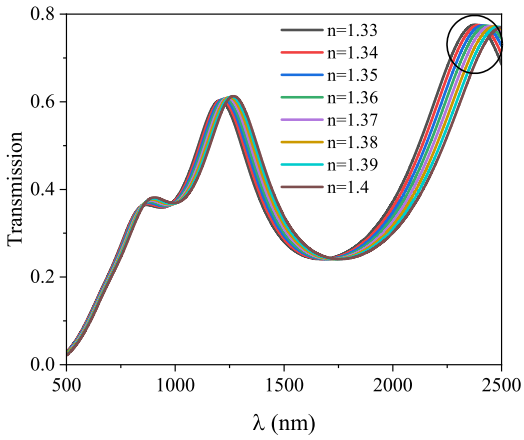
Finally, the VO_2 thickness is increased to 5 nm. Figure 12 presents the transmission spectra and sensitivity analyses for both temperature states. At 30 °C, the sensitivity reaches 1093 nm/RIU, while at 80 °C the sensitivity increases to 1828 nm/RIU. The resonance at the end of the transmission spectrum at 80 °C exhibits the largest wavelength displacement with increasing RI.



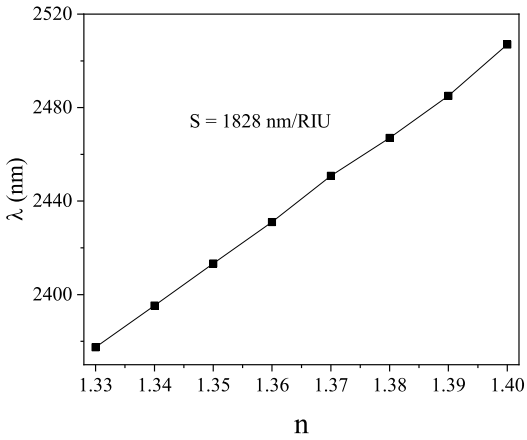
(a) Transmission response at 30 °C.



(b) Sensitivity analysis at 30 °C.



(c) Transmission response at 80 °C.



(d) Sensitivity analysis at 80 °C.

Figure 12. Transmission spectra and sensitivity analyses of the dual-interface MDM structure with 5 nm VO_2 layers at 30 °C and 80 °C.

The sensitivities obtained at 30 °C are 1090, 1076, 1083, and 1093 nm/RIU for VO_2 thicknesses of 2, 3, 4, and 5 nm, respectively. The sensitivity does not vary monotonically over the investigated thickness range. At 80 °C, the corresponding sensitivities are 1699, 1732, 1750, and 1828 nm/RIU, showing a clear increase with increasing VO_2 thickness.

The higher sensitivity obtained in the metallic state can be understood from the strong change in the electrical and optical properties of VO_2 during the insulator-to-metal transition. As the temperature increases, the electrical conductivity of VO_2 rises by several orders of magnitude, accompanied by a pronounced change in its complex RI and dielectric response[18,19]. These changes modify the EM boundary conditions at the metal–dielectric interfaces and consequently alter the propagation and field distribution of the guided plasmonic mode. Because the VO_2 layers are located directly at both interfaces of the sensing core, this temperature-dependent change acts on the mode at both boundaries. In the metallic state, the resulting plasmonic mode is more strongly affected by changes in the optical environment of the sensing medium, so a given variation in RI produces a larger displacement of the resonance wavelength. This behavior explains why the metallic state provides the highest sensitivity throughout the investigated configurations and VO_2 thicknesses. The maximum sensitivity of 1828 nm/RIU obtained at 80 °C therefore results from the combined effect of the dual-interface configuration and the strongly altered optical response of metallic VO_2.

1.1 Comparison with Previous Studies

Table 1 compares the RI sensitivity of the proposed sensor with several previously reported MDM-based plasmonic sensors. The proposed structure achieves a maximum sensitivity of 1828 nm/RIU, which is higher than the sensitivity values reported for the compared structures. In addition to its high sensitivity, the proposed sensor uses a simple planar MDM configuration and provides thermal tunability through the temperature-dependent optical response of ultrathin VO_2 layers. These features allow the sensing response to be controlled through both the spatial configuration and the optical state of the VO_2 layers.

Table 1. Comparison of the RI sensitivity of the proposed sensor with previously reported MDM-based plasmonic sensors.

Reference	Structure	Sensing configuration	Sensitivity (nm/RIU)
Hoang et al.[?]	Ag/SiO_2/Ag MDM	MDM plasmonic metasurface	1109
Hoang et al.[?]	Ag/SiO_2/Ag MDM	MDM plasmonic metasurface	1290
Ghanavati and Karami[?]	Ag–air–Ag MDM	Coupled cavities	1345.45
Ahmed et al.[?]	Ag–SiO_2–Ag MDM	Ag square-block array	1287
Alipour et al.[?]	MDM plasmonic structure	Tunable dual-band MDM	1240
This work	**Ag–VO_2–air–VO_2–Ag MDM**	**Dual-interface VO_2**	**1828**

Discussion

The obtained results show that the position and thickness of the VO_2 layers have a clear effect on the spectral response of the proposed MDM plasmonic sensor. Among the considered configurations, locating VO_2 at both metal–dielectric interfaces provides a higher sensing response than locating the phase-change layer at only one interface. This behavior can be related to the field confinement near the metal–dielectric boundaries of the MDM waveguide. When VO_2 is present at both interfaces, the phase-change material is located at both boundaries of the sensing core, allowing its optical properties to affect the plasmonic response on both sides of the core. As a result, changes in the complex RI of VO_2 have a greater effect on the transmission response and the wavelength shift produced by changes in the sample RI.

The temperature-dependent results further show that the sensing response is higher at 80 °C than at 30 °C. This difference is associated with the change in the optical properties of VO_2 between its insulating and metallic states. The transition modifies the effective permittivity of the VO_2 layers and alters the optical response of the metal–dielectric interfaces. The resulting change in the plasmonic mode affects the spectral resonance and the wavelength shift associated with variations in the sample RI. Therefore, the phase state of VO_2 provides an additional degree of freedom for controlling the sensing response.

The thickness study further shows that the geometrical parameters of the phase-change layers affect the sensor performance. Starting from the reference thickness of 2 nm, the VO_2 thickness is increased to 3, 4, and 5 nm while the layers remain located at both metal–dielectric interfaces. At 30 °C, the sensitivities are 1090, 1076, 1083, and 1093 nm/RIU for thicknesses of 2, 3, 4, and 5 nm, respectively. The sensitivity therefore does not vary monotonically over the investigated thickness range, with a small decrease from 2 to 3 nm followed by an increase at larger thicknesses. In contrast, at 80 °C, the sensitivity increases from 1699 to 1732, 1750, and 1828 nm/RIU as the VO_2 thickness increases from 2 to 3, 4, and 5 nm, respectively. This difference between the two temperature states indicates that the effect of VO_2 thickness depends on its optical state.

The stronger response obtained at 80 °C also becomes more evident when the effect of thickness is considered. For a VO_2 thickness of 5 nm, the sensitivity increases from 1093 nm/RIU at 30 °C to 1828 nm/RIU at 80 °C. This result highlights the combined effect of the temperature-dependent optical properties and geometrical thickness of VO_2. The proposed structure therefore does not rely only on the insulator–metal transition of VO_2; the location and thickness of the phase-change layers also affect the sensing response.

An important feature of the proposed design is its relatively simple planar geometry. The sensing performance is enhanced through the position and thickness control of ultrathin VO_2 layers rather than through a complicated cavity or multilayered geometry. This configuration maintains a compact MDM structure while allowing the optical properties of the phase-change material to affect the plasmonic sensing response. The obtained results therefore show that phase-change material engineering can be combined with a simple MDM configuration to achieve high RI sensitivity.

Overall, the results confirm that the sensing performance depends on the position, phase state, and thickness of the VO_2 layers. The configuration with VO_2 at both metal–dielectric interfaces and a thickness of 5 nm provides the highest sensitivity among the investigated structures, reaching 1828 nm/RIU at 80 °C. These findings show that simultaneous control of the optical state and geometrical thickness of VO_2 provides an effective approach for improving the RI response of compact MDM plasmonic sensors.

Methods

1.2 Numerical Model

The proposed MDM plasmonic sensor is modeled using the finite element method (FEM). The structure is defined in the x–y plane and consists of two silver (Ag) layers separated by an air core. Ultrathin VO_2 layers are located at the metal–dielectric interfaces. The air core acts as the sensing region and is filled with samples having RI values ranging from 1.33 to 1.40. The initial thickness of the VO_2 layers is 2 nm, while thicknesses of 3, 4, and 5 nm are considered for thickness optimization.

The structure is considered physically infinite along the z-axis. A TM-polarized incident wave with an electric-field amplitude of 50 V/m is applied along the x-axis. The EM response is calculated over the selected wavelength range, and the transmission spectrum is obtained from the transmitted field.

1.3 Material Properties

Silver is used as the metallic cladding of the MDM structure, while air forms the dielectric core and sensing region. The wavelength-dependent optical response of silver is described by the Drude model given in Eq. 1, with the corresponding model parameters adopted from our previous work[12].

The optical response of VO_2 is described using wavelength-dependent complex RI data reported by Oguntoye et al.[18] for its insulating and metallic states at 30 and 80 °C, respectively. The real and imaginary parts of the RI are used to represent the temperature-dependent optical response of the VO_2 layers in the numerical model. The resulting optical properties are assigned to the VO_2 layers for the corresponding temperature states.

The RI of the sensing medium is varied from 1.33 to 1.40 to evaluate the wavelength response of the proposed structure. For each RI value, the corresponding transmission spectra is calculated and used to determine the resonance wavelength and RI sensitivity.

1.4 Numerical Procedure

A triangular finite-element mesh is employed throughout the computational domain. The mesh is refined around the ultrathin VO_2 layers and the metal–dielectric interfaces. A sufficiently fine mesh is also used in the sensing region to obtain the transmission response accurately.

Appropriate boundary conditions are applied to the boundaries of the computational domain. The structure is defined in the x–y plane and is considered physically infinite along the z-axis. The EM response is calculated for each considered VO_2 state and sensing-medium RI.

A mesh-convergence analysis is performed to ensure that further mesh refinement does not produce a significant change in the calculated resonance wavelength. The mesh is considered sufficiently refined when the variation in the resonance wavelength remains below 1%.

For each VO_2 temperature state, the RI of the sensing sample is varied from 1.33 to 1.40. The corresponding transmission spectrum is calculated for each RI value, and the resonance wavelength is extracted from the selected transmission peak or dip. The wavelength shifts are then used to calculate the RI sensitivity.

1.5 Sensitivity and Performance Parameters

The RI sensitivity is calculated using Eq. 2, where S is the RI sensitivity in nm/RIU, $\Delta\lambda$ is the resonance wavelength shift and Δn is the corresponding change in the RI of the sensing medium. The resonance wavelength is plotted as a function of RI and the slope of the resulting linear fit is taken as the RI sensitivity.

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Author contributions statement

F.L. conceived the study, designed the plasmonic structure, performed the numerical simulations, analyzed the results and wrote the original manuscript. R.K. contributed to the interpretation of the results, reviewed the manuscript and provided scientific guidance. All authors discussed the results, critically revised the manuscript and approved the final version.

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