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Ahmad Azuad Yaseer (✉ ahmadazuad@iut-dhaka.edu)

Islamic University of Technology <https://orcid.org/0000-0003-2836-6920>

Md. Farhad Hassan

Islamic University of Technology

Infiter Tathfif

Islamic University of Technology

Kazi Sharmeen Rashid

Islamic University of Technology

Rakibul Hasan Sagor

Islamic University of Technology

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Plasmonic Refractive Index Sensor Optimized for Color Detection

Ahmad Azuad Yaseer*, Md. Farhad Hassan, Infiter Tathfif, Kazi Sharmeen Rashid, and Rakibul Hasan Sagor

Department of Electrical and Electronic Engineering,
Islamic University of Technology, Gazipur-1704, Bangladesh

*Email: ahmadazuad@iut-dhaka.edu

Abstract

In this paper, a six cavity-based metal-insulator-metal plasmonic sensor is proposed. The designed sensor can detect six primary colors in the visible wavelength. Moreover, the proposed sensor can also sense the change in the refractive index. An initial sensitivity of 648.41 nm/RIU and figure of merit of (FOM) 141.29 are found based on the transmittance profile extracted through the two-dimensional (2D) finite element method (FEM). The structural parameters are optimized to maximize the performance of the modeled device both as a color filter and a refractive index sensor. The optimized FOM, FOM* and sensitivity are recorded as 218.80, 4.771×10^4 , and 865.31 nm/RIU, respectively. Due to high FOM and FOM*, this sensor is expected to be utilized as a color filter in various sectors, such as medical, industrial, and forensic, where the light of a particular wavelength is mandatory.

Keywords— Finite Element Method (FEM), Color Filter, Refractive Index Sensor, Surface Plasmon Polaritons.

1 Introduction

In recent times, color filters have become one of the vital elements in organic light-emitting diodes, digital projectors, digital photography, and display units of computerized systems. Color filters can deal with specific wavelengths of interest or filter white light into individual colors. Researchers are continuously searching for a method to produce low-cost, compact, and transmission-efficient color filters comparing to traditional pigment-based printing [1–5]. One such technique can be using plasmonic resonators incorporating surface plasmon polaritons (SPPs), which can couple incident light into electromagnetic modes passing through the metal-insulator surface [6, 7]. This concept of SPPs has already been utilized to produce couplers [8, 9], splitters [10, 11], demultiplexers [12, 13], sensors [14, 15], switches [16, 17], filters [18, 19], and color filters [20–22].

Color filters based on SPPs are researched through different Metal-Insulator-Metal (MIM) schematics. Diest *et al.* [20] placed two slits into the waveguide and distinguished three colors - red, green, and blue. Incorporating six unequal square cavities, Butt *et al.* [22] filtered white colors into six colors and reported a maximum sensitivity of 700 nm/RIU. Zhang *et al.* [21] demonstrated a multi-band four-mode color filter possessing an ellipse resonator and recorded the highest sensitivity of 608 nm/RIU and figure of merit (FOM) of 105.02.

In this work, a new schematic of the MIM color filter is proposed using six rectangular cavities. This structure is found to filter out six basic colors with

a maximum sensitivity of 865.31 nm/RIU and FOM of 218.80. The numerical computation of the proposed structure is done utilizing the 2D-Finite Element Method (FEM) of the COMSOL Multiphysics Software.

This paper has been segmented into several sections to explain the schematic and analyze the results concisely. [Schematic Design and Methodological Study](#) explains the theoretical and mathematical relation. [Sensing Procedure and Result Analysis](#), demonstrates the color sensing and optimization procedures. The fabrication procedures have been demonstrated in [Fabrication Technique](#). [Conclusion](#) provides a synopsis of the entire paper.

2 Schematic Design and Methodological Study

Figure 1: Two-dimensional schematic design of the proposed sensor.

The schematic design of the proposed sensor is presented in [Figure 1](#), where the orange color represents silver, and the white color denotes air. The suggested MIM refractive index (RI) sensor incorporates six rectangular cavities of different lengths. Three cavities of length L_1 , L_2 , and L_3 are placed on the

upper side of the waveguide, whereas the other three cavities of length L_4 , L_5 , L_6 are placed on the lower side. The cavities are placed at a similar distance $D1$ from the waveguide, where the distance between each cavity is $D2$. The value of the structural parameters are stated in [Table 1](#).

Table 1: Values of each schematic parameter of the proposed structure.

Parameters	Symbol	Unit (nm)
Length of the cavity to detect violet color	$L1$	125
Length of the cavity to detect blue color	$L2$	150
Length of the cavity to detect green color	$L3$	165
Length of the cavity to detect yellow color	$L4$	190
Length of the cavity to detect orange color	$L5$	210
Length of the cavity to detect red color	$L6$	225
Width of the waveguide and the cavities	W	100
Distance between the waveguide and the cavities	$D1$	40
Distance between two cavities	$D2$	300

In this paper, silver is chosen as the plasmonic material to provide an electromagnetic response within the near-infrared range due to possessing the smallest imaginary part of relative permittivity [\[22\]](#). This permittivity is frequency-dependent and is characterized by Lorentz-Drude Model through an equation defined as [\[23\]](#),

$$\hat{\epsilon}(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - i\Gamma_0)} + \sum_{n=1}^6 \frac{f_n \omega_n^2}{\omega_n^2 - \omega^2 + i\omega\Gamma_n} \quad (1)$$

where, $\hat{\epsilon}(\omega)$ denotes the complex relative permittivity. ω_p , and ω_n designate the plasma frequency, and the resonant frequency, respectively. Furthermore, Γ_0 , Γ_n , and f_n denote the collision frequency, the damping frequency, and the oscillator strength, respectively.

Furthermore, parts of incident waves are coupled into cavities to reach the

output port due to the excitation of fundamental mode at the input port. This dispersion relation is expressed as [24],

$$\tanh\left(-\frac{ik_{c1}}{2}\omega\right) = -\frac{\varepsilon_{silver}k_{c2}}{\varepsilon_{air}k_{c1}}, \quad (2)$$

where, k_{c1} , and k_{c2} are momentum conservations defined as,

$$\begin{cases} k_{c1}^2 = \varepsilon_{air}k_0^2 - \beta^2, \\ k_{c2}^2 = \varepsilon_{silver}k_0^2 - \beta^2, \end{cases} \quad (3)$$

where, the dielectric constant of silver and air are represented as ε_{silver} , and ε_{air} , respectively. Furthermore, the resonance wavelength, λ_{res} is derived as [24],

$$\lambda_{res} = \frac{2\text{Re}(\eta_{eff})L}{M - \frac{\psi_r}{\pi}}, \quad M = 1, 2, 3, \dots, \quad (4)$$

where, L is the effective resonance length, M is the mode integer, ψ_r is the phase shift of the beam caused by reflection at one end of the cavity and η_{eff} is the effective refractive index. The real part of η_{eff} can be calculated from,

$$\text{Re}(\eta_{eff}) = \sqrt{\left[\varepsilon_{silver} + \left(\frac{k}{k_0}\right)^2\right]}, \quad (5)$$

where, k_0 is the wavenumber.

3 Sensing Procedure and Result Analysis

3.1 Sensing Procedure

From Equation 4, $\lambda_{res} \propto L$ while effective refractive index and mode are fixed. Different wavelengths of light in the visible color range produce different colors. Colors can easily be detected if the resonance wavelength is known. Therefore, the proposed sensor contains six different-length cavities to detect six basic colors – violet, blue, green, yellow, orange, and red. Different resonance wavelengths confine in the specific cavity. The E -field confinement of those resonance wavelengths has been depicted in Figure 2. The transmittance curve (shown in Figure 3) exhibits six sharp resonance dips at six different resonance wavelengths at refractive index, $\eta = 1$. Table 2 provides a comparison between these resonance wavelengths of six colors and their typical wavelength range [22]. Therefore, the detection of those specific colors is established.

Figure 2: E -field confinement in rectangular cavities of length (a) L_1 , (b) L_2 , (c) L_3 , (d) L_4 , (e) L_5 , and (f) L_6 at initial parameters.

Figure 3: Transmittance spectrum of the proposed sensor at initial parameters.

Table 2: The wavelength range for six visible basic colors.

Color	Violet	Blue	Green	Yellow	Orange	Red
Wavelength range of color (nm) [22]	380 - 450	450 - 495	495 - 570	570 - 590	590 - 620	620 - 750
Resonance wavelength of proposed sensor (nm)	441.91	489.75	520.36	572.38	617.19	651.17

The performance of a RI sensor can be measured through two significant factors - sensitivity and figure of merit which are determined as,

$$\text{Sensitivity}(S) = \frac{\text{Change in Wavelength } (\Delta\lambda)}{\text{Change in Refractive Index } (\Delta\eta)}, \quad (6)$$

and,

$$\text{Figure of Merit } (FOM) = \frac{\text{Sensitivity } (S)}{\text{Full Width at Half Maximum } (FWHM)}. \quad (7)$$

3.2 Result Analysis for Initial Framework

Figure 4: (a) Transmittance vs. wavelength curve for different values of refractive index, η . (b) Resonance wavelength vs. refractive index curve for initial framework.

To calculate the sensitivity of the proposed structure, the refractive index is varied from 1 to 1.01, with an interval of .005, and redshift is observed at resonance dips (Figure 4a). Furthermore, the sensitivity and FOM have been calculated, and the existence of positive slopes in Figure 4b substantiates the redshift. The highest sensitivity and FOM are found as 648.41 nm/RIU and 141.29 at $\eta = 1$. The proposed structure is optimized in terms of FOM in the later section to obtain superior filter performance.

3.3 Optimization of Parameter $D2$ and $D1$

The optimization of the proposed sensor starts by varying $D2$ from 200 nm to 350 nm, with an interval of 50 nm, while keeping $D1$ constant at 40 nm. The parametric value of $D2$ more than 300 nm shifts the resonance dip from desired visible color range and distorts the transmittance curve (Figure 5a).

Figure 5: (a) Transmittance vs. wavelength curve for different values of $D2$. Resonance wavelength vs. refractive index curve for (b) $D2 = 300$ nm. (c) $D2 = 250$ nm, and (d) $D2 = 200$ nm.

Redshift is observed for the remaining values of $D2$, which is indisputable from positive slope for each resonance dip demonstrated in Figure 5b – Figure 5d. Comparing the FOM, $D2 = 200$ nm is not a suitable option as the FOM of each dip is decreased (Figure 5d). Furthermore, for $D2 = 250$ nm, FOM of *Dip I*, *Dip III*, *Dip VI* increase while others decrease. Nonetheless, $D2 = 250$ nm is chosen as it provides higher FOM to detect violet light using *Dip I*. Violet light is prioritized in this particular scenario as recent works explored the use of the

violet light in various cases such as fungal study [25], dental bleaching [26], forensic science [27], surgical management [28].

Figure 6: (a) Transmittance vs. wavelength curve for different values of $D1$. Resonance wavelength vs. refractive index curve for (b) $D1 = 40$ nm and (c) $D1 = 50$ nm.

Figure 6a resembles the transmittance vs. wavelength curve for different values of $D1$ ranging from 30 nm to 60 nm, with an interval of 10 nm. For $D1 = 30$ nm, the resonance dip for orange color (621.37 nm) shift from the desired wavelength range (Table 2). Furthermore, when $D1 \geq 60$ nm, the resonance dips are not so sharp and almost diminishing. Hence, $D1 = 30$ nm and $D1 = 60$ nm cannot be taken as optimized values. Figure 6b and Figure 6c illustrate the

resonance wavelength vs. refractive index curves for $DI = 40$ nm and $DI = 50$ nm, respectively. It is observed that $DI = 50$ nm provides higher FOM along with higher sensitivity compared to $DI = 40$ nm. Hence, the optimized value for DI is settled as 50 nm.

Figure 7: Transmittance spectrum of the proposed sensor at optimized parameters.

Figure 8: E-field confinement in rectangular cavities of length (a) L_1 , (b) L_2 , (c) L_3 , (d) L_4 , (e) L_5 , and (f) L_6 at optimized parameters.

Finally, [Figure 7](#) displays the transmittance vs. wavelength curve for the optimized parameters, where the legend indicates the resonance wavelengths. Furthermore, [Figure 8](#) portrays the E -field confinement in the cavities for those resonance wavelengths. Moreover, [Table 3](#) epitomizes the change of sensitivity and FOM before and after the optimization process. Therefore, the highest sensitivity and FOM offered by the proposed sensor are 865.31 nm/RIU and 218.80, respectively.

Table 3: Summary of the optimization process.

Dip	Sensitivity (nm/RIU)		FOM	
	D2 = 300 nm D1 = 40 nm	D2 = 250 nm D1 = 50 nm	D2 = 300 nm D1 = 40 nm	D2 = 250 nm D1 = 50 nm
	(Initial Value)	(Optimized Value)	(Initial Value)	(Optimized Value)
<i>Dip I</i>	309.95623	409.15779	55.349	68.68
<i>Dip II</i>	427.47811	402.58958	70.90	68.24
<i>Dip III</i>	430.35171	460.33512	79.931	97.81
<i>Dip IV</i>	526.85344	804.0032	141.285	177.927
<i>Dip V</i>	531.96931	865.30653	107.57	218.80
<i>Dip VI</i>	648.31874	409.36305	97.90	90.56

In different literature, another performance metric FOM* is measured at a defined wavelength as [\[29\]](#),

$$FOM^* = \frac{\Delta R}{R\Delta\eta} = \frac{|R_{\eta=1.005} - R_{\eta=1}|}{.005 \times R_{\eta=1}}. \quad (8)$$

where, ΔR stands for variation in reflection intensity caused by variation in refractive index ($\Delta\eta$) and R is the reflection rate in the sensor.

The measured FOM* is plotted in the [Figure 9](#), where three FOM* peaks are observed. The highest FOM* is found as 4.771×10^4 . Therefore, the proposed sensor surpasses recent plasmonic-based RI sensors in terms of FOM

Figure 9: FOM* at optimized parameters.

and FOM* (Table 4).

Table 4: Performance comparison of the proposed sensor with recent plasmonic-based RI sensors.

Reference	FOM	FOM*
[22]	-	191.6
[30]	-	2.73×10^4
[31]	-	3.51×10^4
[32]	-	4.05×10^4
[33]	16.7	-
[21]	105.02	-
[34]	159.6	-
Proposed sensor	218.8	4.771×10^4

4 Fabrication Technique

The structural parameters have been fixed considering vertically smooth sidewalls and nearly 90 corners offered by the nanoimprint lithography fab-

Figure 10: Fabrication technique of the proposed sensor.

rication process [35]. The whole procedure is illustrated in Figure 10, where the silicon wafer is considered as the substrate. The first step is imprinting the blueprint of the sensor over the resin using a stamp (Figure 10a). The undesired resin is then removed from the compressed area through O₂ plasma etching (Figure 10b). Subsequently, electron beam evaporation (Figure 10c) deposits the silver on the substrate, followed by eliminating residual resin through the lift-off technique (Figure 10d).

5 Conclusion

In summary, the transmission spectra of the proposed structure consisting of six rectangular cavities are scrutinized through the finite element method. The resonance dips achieved through simulation can detect six basic colors used in various medical, photonics, industrial applications. Alternatively, this color detection-focused optimized structure can also be used as an RI sensor with maximum sensitivity, FOM, and FOM* of 865.31 nm/RIU, 218.80, and 4.771×10^4 , respectively. Due to the implementation of a low-cost and high throughput fabrication process along with satisfactory performance, the proposed struc-

ture will be a perfect choice both as a color detector and a RI sensor.

Declarations

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Conflict of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Availability of Data and Material

Not available.

Code Availability

Not available.

Authors' Contributions

- Ahmad Azuad Yaseer: Conceptualization, Methodology, Software, Writing Original Draft.
- Md. Farhad Hassan: Investigation, Supervision.
- Infiter Tathfif: Validation, Formal Analysis, Writing Review and Editing, Visualization.
- Kazi Sharmeen Rashid: Resources, Writing Review and Editing.
- Rakibul Hasan Sagor: Supervision, Project administration.

Ethics approval

This is an observational and simulation-based study. No ethical approval is required.

Consent to participate

Not applicable.

Consent for publication

This manuscript has not been published and is not under consideration for publication elsewhere. All authors have approved the manuscript and agree with its submission.

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