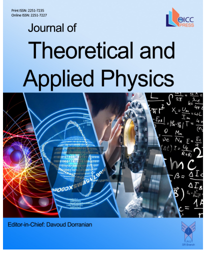

Volume 19, Issue 3, 192534 (1-4)

Journal of Theoretical and Applied Physics (JTAP)

https://doi.org/10.57647/j.jtap.2025.1903.34

Two dimensional plasmonic and all dielectric metasurface for Laser induced fluorescence enhancement

Noor Dhyaa Abdulameer[1], Lazem Hassan Aboud[1], Nizar Salim Shnan[1,2,*]

[1] *Department of Laser Physics, College of Science for Woman, University of Babylon, Babylon, Iraq.*
[2] *Magneto-Plasmonic Lab, Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran.*

*Corresponding author: nizarflifl@yahoo.com

Original Research

Received:
6 April 2025
Revised:
19 June 2025
Accepted:
25 June 2025
Published online:
30 June 2025

Abstract:

We have experimentally examined the effect of all dielectric metasurface's localization in plasmonic hot spots over the two dimensional periodic structure onto the laser induced fluorescence. The host medium of the dye achieved by spin coating of the Rh6G over the two dimensional MgF_2/Gold structure and the LIF signal records in visible region by nanosecond Green laser pumping. Our results indicate that the localized field enhancement due to Electric and Magnetic dipoles resonance of all dielectric media and also refractive index localization effect can boost laser induced fluorescence in the visible region until 5 times in the comparison with the sample without bottom dielectric layer.

Keywords: Magneto-plasmonics; Plasmon; Laser induced fluorescence; Surface lattice resonance; Metasurfaces; Light localization

1. Introduction

Laser induced fluorescence (LIF) measurement introduces for spectroscopic and collision studies in material science, oil study and diagnostics probes in these decades [1]. BecauseFluorescence spectroscopy is mainly concerned with electronic and vibrational states, these kinds of signals are weak and must be amplified if anyone wants to use diagnostic methods.

Until now scientists reportseveral methods to amplify this signal by new nanophotonic or micro photonic construction [2], near field usage by plasmonic localization [3] or metasurfaces based on metallic and dielectric structures or media [4] as adjustable or tunable methods respectively.

Metallic nanoparticles and thus plasmon due to these media, dramatically modify the spontaneous emission of nearby fluorescent molecules and materials due to near field localization [5, 6].

The heightened electromagnetic fields near metallic surfaces due to localized plasmon resonances and propagating SPPs also enhance the emission of fluorescent species placed in the near field. However, for molecules in contact with the metallic surface, care has to be taken in order not to quench the fluorescence via non-radiative transitions. Thus, for the observation of enhanced fluorescence, often a nanometer-thin dielectric spacer layer is required to prohibit non-radiative excitation transfer from the molecule to the metal [7]. Fluorescence results from excitation of the molecule by the incidentfield- which can show significant enhancement due to a plasmon resonance of the gold particle-and the subsequent emission of radiation by the molecule, which is determined by the balance between radiative and non-radiative decay processes [8]. Since non-radiative energy transfer to the nanoparticle can take place for small distances between the molecule and the sphere, a decrease inemission probability can be expected, despite an increase in excitation rate due to the enhanced local field [9].

Even though the advantage of near-field enhancement by plasmonic nanoparticles or nanostructures, the large ohmic loss, drift scientists to use all dielectric media to enhance LIF [10, 11]. By the way, to use the signal in practical point of view, it must be amplifying instead of controlling the ohmic lossa nd surface lattice resonance (SLR) which is possible by surrounding metallic layer by some dielectric top layers [12].

In this article, we use two dimensional (2D) plasmonic and all dielectric metasurfaces by its straightforward manufacturing, reasonable price, good efficiency, and the ability to be easily duplicated at large proportions. By integrating the plasmonic capabilities of 2D structures, we were able to achieve active control over the SLR, as well as the switching effect, which can be beneficial in a variety of switching and sensing applications [13, 14].

2. Experimental part

To obtain the metasurface enhanced LIF, we create two flexible 2D structures by soft nano imprint lithography technique onto polydimethylsiloxane (PDMS). The main structure of the molds has been changed in a periodic pattern with a diameter of 3 µm, and the gap between each pattern extends to about 400 to 600 nm, which makes it suitable for excitation within the visible light range (Fig. 1 (a)). Two dimensional plasmonic structure as bottom substance is a periodic array of gold layers, it promotes SLR, which is caused by the coupling of diffractive waves and the localized plasmon resonance associated with individual nanoparticles at a wavelength comparable to their period.

During the fabrication process, the PDMS is prepared with a mixture of curing agent, then the main layer is coated and degassed by vacuum at 10^{-2} mbar, then heated on a heater during two time steps, and coated with a thin layer of MgF_2 (15 nm) and Gold layer (30 nm) using a sputtering machine, and the dye Rh6G is added using a spin-coating device in the last step in two samples.

When the samples dry, we record LIF by using the second harmonic of the Nd: YAG laser, and at an angle of 90°, the fluorescence is recorded via a spectrometer covering all visible spectra with four different excitation energies from 0.13 to 1.95 mJ (Fig. 1 (c))

3. Results and discussion

As shown in Fig. 1 (a), we have SEM image of the main fabricated flexible substrate with periodic structure which can supports surface lattice resonance. In the main LIF window, we must have Electric and magnetic dipole coupling in the fabricated sample onto the PDMS substrate which confirms in the second part of this figure by Gold thin layer over the substrate (Fig. 1 (b)). In the primary LIF window, we can see two prominent peaks in the spectrum which can comes from the coupling of ED and MD of each motif in the unit cell with diffraction order of the periodic array.

As mentioned above, we must use another thin layer bottom or top of this Gold layer to enhance light localization and thus LIF improvement due to metasurfaces effect. For this purpose, we have MgF_2 metasurface bottom of plasmonic layer and record the LIF signal in different input power as shown in Fig. 1 (d). This all dielectric and metallic metasurface with periodic structure can enhance LIF, until 70000 in the intensity, which means we have five times strongest LIF signal.

It is obvious that the signals according to ED and MD resonance affected by MgF_2 layer by decrease and increase in each of them respectively. To get more sense about this fact,

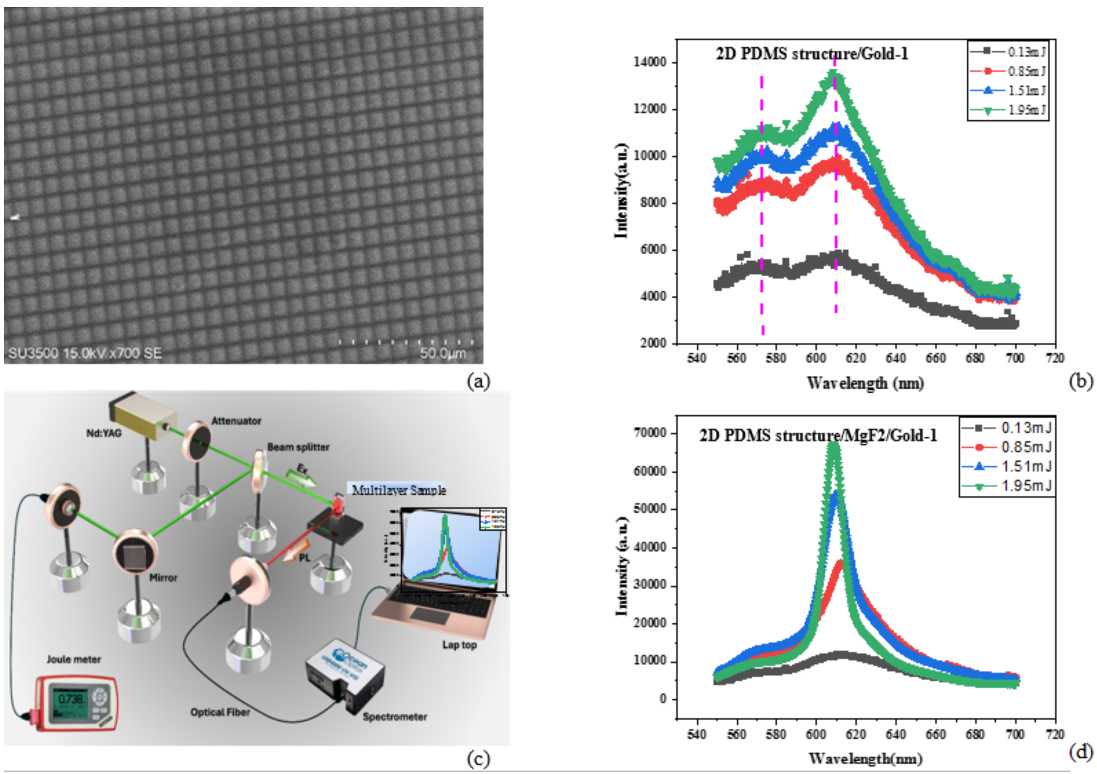

Figure 1. (a) SEM image of the main PDMS substrate, (b) LIF signal of the main plasmonic sample in different energies, (c) Schematic diagram of the experimental setup and (d) LIF signal of the metasurface/plasmonic sample in different energies.

we simulate the structure by finite difference time domain and the electric field distribution at the resonance wavelength of 550 nm was calculated. The simulated structure consists of a 3×3 array of unit cells arranged on a PDMS substrate, and MgF_2 and Au films' thickness was assumed to be 10 and 35 nm, respectively. The refractive index of the PDMS, MgF_2, and Au materials was taken from the Schneider et al. [15], Dodge et al. [16], and Johnson and Christy [17] database, respectively. Figure 2 illustrates the refractive index profile of the simulated 2D metsurface/-plasmonic structure and presents the corresponding electric field distribution at the resonance wavelength of 550 nm.
PDMS is a dielectric material that serves as the simulated structure's substrate. A thin layer of MgF_2 will significantly impact the electric field distribution due to its ability to polarize in response to an external electric field. This thin layer can enhance or modify the electric field distribution due to its dielectric properties. The gold layer (35 nm thick) is conductive and will behave as a perfect electric conductor at optical frequencies. It will reflect incident electromagnetic waves and can support SPPs, which can enhance the local electric field in its vicinity. When an external electric field is applied, the MgF_2 layer will become polarized, creating bound charges at its interfaces with both PDMS and gold. This polarization can modify the local electric field distribution, particularly at the boundaries.
The presence of MgF_2 layer can lead to constructive interference of the electric fields and can enhance the electric field in certain regions of the grating structure. Further, surface plasmons can be excited at the interface between the gold and MgF_2, leading to localized enhancements in the electric field, and lead to hotspots where the electric field is significantly stronger (Fig. 2 (b)). The polarization in the MgF_2 layer and any dipole moments induced by external fields will affect how charges distribute within the dielectric layers. The presence of these induced dipoles

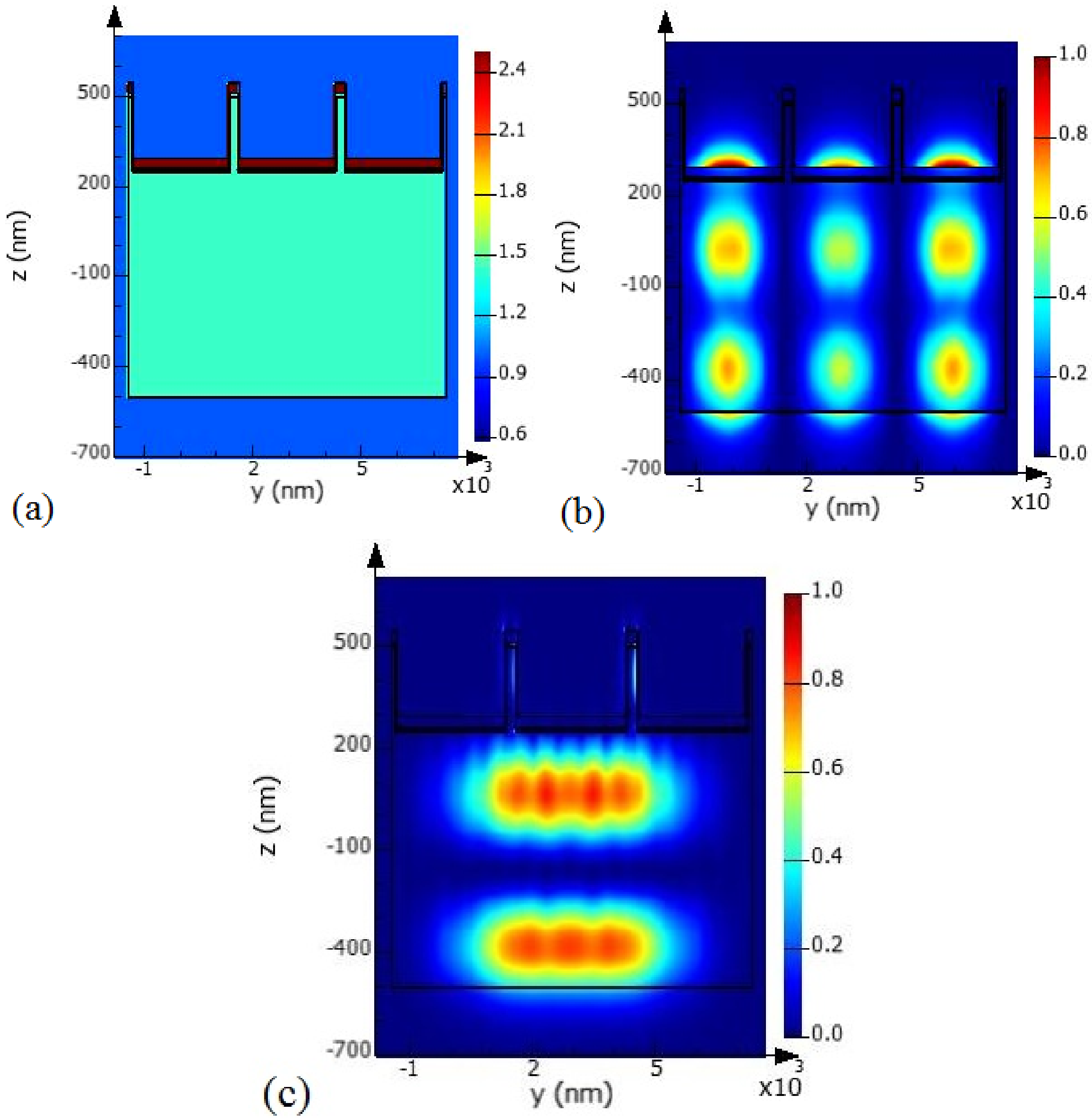

Figure 2. (a) The refractive index profile of the simulated two-dimensional structure, and the electric field distribution (b) at the resonance wavelength of 550 nm, and (c) at the non-resonant wavelength of 625 nm.

can lead to localized variations in the electric field. In addition, in the wavelength far from resonance ones, we don't have our mainly localization in dielectric or plasmonic layer (Fig. 2 (c)) which is confirmed why we don't have amplification in other non-resonance wavelengths.
In conclusion, the intermediate MgF_2 layer fundamentally alters the electric field distribution in the proposed structure. It introduces additional polarization effects, enhances field localization, and improves coupling to surface plasmons, leading to dynamic electric field distribution compared to a configuration without this dielectric layer. This can have significant implications for applications in photonics, sensing, and other areas where control over electric fields is critical.

4. Conclusion

We fabricate flexible all dielectric two dimensional structures based on PDMS/MgF_2/Gold/Rh6G multilayer for LIF signal. Green light nanosecond pulsed laser were used as the source of excitation and the fluorescence signal recorded by spectrometer in the visible region. Our results show two mainly peaks in the fluorescence spectrum due to the ED and MD modes in the sample and five times amplification in ED mode LIF due to light localization by all-dielectric metasurfaces bottom of metallic Gold layer. This amplification by dielectric localization and lossless structure can open new insight in LIF signal enhancement systems.

Authors Contribution
Noor D. Abdulameer and N. S. Shnan produce the samples and write the main text, Lazem Hassan Aboud advised the project and S. M. Hamidi supervised all of the work.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A. Ehn, J. Zhu, X. Li, and J. Kiefer. "Advanced Laser-Based Techniques for Gas-Phase Diagnostics in Combustion and Aerospace Engineering.". *Applied Spectroscopy*, **71**(3), 2017.

[2] D. F. McMillen, K. E. Lewis, G. P. Smith, and D. M. Golden. "Quantitative laser Diauostics for Combustion Chemistry and Propulsion.". *J. Phys. Qhem.*, **86**(709), 1982.

[3] A. Pascal, B. Palash, and N. Lukas. "Enhancement and quenching of single-molecule fluorescence.". *Phys. Rev. Lett.*, **96**:113002, 2006. DOI: https://doi.org/10.1103/PhysRevLett.96.113002.

[4] R. Antoine, P. F. Brevet, H. H. Girault, D. Bethell, and D. J. Schiffrin. "Surface plasmon enhanced non-linear optical response of gold nanoparticles at the air/toluene interface.". *Chem. Commun.*, pages 1901–1902, 1997.

[5] F. Tam, G. P. Goodrich, B. R. Johnson, and N. J. Halas. "Plasmonic Enhancement of Molecular Fluorescence.". *Nano letters*, **7**(2), 2007.

[6] K. Leosson, T. Nikolajsen, A. Boltasseva, and S. I. Bozhevolnyi. "Long-range surface plasmonpolariton nanowire waveguides for device applications.". *Opt. Express*, **14**(1):314319, 2006.

[7] W. Deng, F. Xie, H. Baltar, and E. Goldys. "Metal-enhanced fluorescence in the life sciences: Here, now and beyond.". *Phys. Chem. Chem. Phys.*, **15**:15695, 2013.

[8] H. Mbarak, S. M. Hamidi, E. Mohajerani, and Y. Zaatar. "Electrically driven flexible 2D plasmonic structure based on a nematic liquid crystal.". *Journal of Physics D: Applied Physics*, **52**(41):415106, 2019.

[9] N. D. Abdulameer, N. S. Shnan, L. H. Aboud, and S. M. Hamidi. "Two dimensional MgF_2 metasurface for Laser induced fluorescence enhancement.". *Optical and Quantum Electronics*, 2025.

[10] H. Mbarak, R. Taheri Ghahrizjani, S. M. Hamidi, E. Mohajerani, and Y. Zaatar. "Reversible and tunable photochemical switch based on plasmonic structure.". *Scientific Reports*, **10**(1):1–7, 2020.

[11] V. K. Hsiao, Y. B. Zheng, B. K. Juluri, and T. J. Huang. "Light-Driven Plasmonic Switches Based on Au Nanodisk Arrays and Photoresponsive Liquid Crystals.". *Advanced Materials*, **20**(18):3528–3532, 2008.

[12] S. Khatua, W. Chang, P. Swanglap, J. Olson, and S. Link. "Active Modulation of Nanorod Plasmons". *Nano Letters*, **11**(9):3797–3802, 2011.

[13] M. J. Moradi, S. M. Mohseni, S. Mahmoodi, D. Rezvani, N. Ansari, S. Chung, and J. Akerman. "Au/NiFemagnetoplasmonics: Large enhancement of magneto-optical Kerr effect for magnetic field sensors and memories.". *Electronic Materials Letters*, **11**(3):440–446, 2015.

[14] S. F. Haddawi, M. Mirahmadi, H. Mbarak, A. K. Kodeary, M. Ghasemi, and S. M. Hamidi. "Footprint of plexcitonic states in low-power green–blue plasmonic random laser.". *Applied Physics A*, **125**(12), 2019.

[15] F. Schneider, J. Draheim, R. Kamberger, and U. Wallrabe. "Process and material properties of polydimethylsiloxane (PDMS) for Optical MEMS.". *Sensors and Actuators A: Physical*, **151**(2):95–99, 2009.

[16] M. J. Dodge. "Refractive properties of magnesium fluoride.". *Applied Optics*, **23**(12):1980–1985, 1984.

[17] P. B. Johnson and R. W. Christy. "Optical Constants of the Noble Metals.". *Physical Review B*, **6**:4370–4379, 1972.