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Optical Nano-Antenna for Molecular Sensing

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Abstract: ***Optical Nano-antennas represent a promising innovation for highly sensitive molecular detection at the nanometer scale. With the aid of plasmonic amplification, field localization, and near-field interactions, they allow for immediate and label-free monitoring of molecules in minute quantities. This article focuses on a detailed analysis of optical nano-antennas employed in molecular sensing applications, with special attention given to their theory, fabrication, simulation, and real-time implementation through COMSOL Multiphysics and Lumerical FDTD. The design optimization of dual elliptical gold nanoantennas, composite MDM, and Magnetoplasmonic antennas is addressed. Performance criteria such as field amplification($\geq 10^4$),bulk and surface sensitivities (maximum 530 nm/RIU), and figure of merit (FOM ~ 8.1–30) were examined.***

I. INTRODUCTION

These Nano-antennas can be employed to detect the interaction of light with molecules by converting freely propagating optical radiation into localized near-field components.It has recently been shown that plasmonic or magnetoplasmonic antennas can enhance the vibrational signature of a molecule by up to 10–12 orders of magnitude using field and scattering enhancement mechanisms. This can be achieved simultaneously with hybrid nanostructures, such as MDM nanorods and ellipsoidal gold dimers, which can achieve molecular fingerprinting. The key motivation for developing such systems is to enable label-free detection of biomolecules, such as proteins and polymers.

II. RELATED WORK

Field-Enhanced Molecular Scattering: Rezus and Selig verified that field-enhanced molecular scattering scales with the fourth power of local field enhancement ($|f|^4$) in SEIRA setups, where the vibrational resonances could be completely attributed to the scattering phenomena and not absorption

Elliptical Plasmonic Antennas: Verma et al. maximized the performance of dual gold elliptical nanoantennas, providing 530 nm/RIU bulk sensitivity and FOM of 8.1, where the aspect ratio and height were the major factors

Hotspot Selective Binding: Zhang et al. developed Ti- coated Au dimers to selectively manipulate hotspots, enabling selective binding of molecules, six times better than individual nanorods

Integrated QCL-based Sensors: Dey et al. implemented MDM plasmonic antennas (Au-SiO_2-Au) on quantum cascade laser surfaces, confining the optical modes to a region 12 times smaller than the wavelength and a local electric field enhancement factor of 4000

Magnetoplasmonic Phase-Controlled Detection: Maccaferri et al. fabricated nanostructured ferromagnetic antennas that provided surface sensitivities an order of magnitude higher (≈0.8 ag/antenna) through light polarization phase manipulation

III. METHODOLOGY

A. Antenna Design and Materials

Structure: Elliptical dimer antenna (Au), magnetoplasmonic disk (Ni), and metamaterial-based dual- mode nanorod (Au-SiO2-Au).

Dielectric Substrates: Quartz glass with a refractive index of n = 1.45 or pure silica (n = 1.45).

Elliptical Dimer: semi-major axis a = 100 nm, semi-minor axis b = 10-40 nm, height h = 40 nm, gap = 10 nm.Metamaterial Dimer

B. Simulation Setup

Software Used: COMSOL Multiphysics (Finite Element Method) and Lumerical FDTD.

Parameters: Light source with λ_res = 1550 nm incident upon it; mesh less than $\lambda/20$.

Boundary Condition: Perfectly Matched Layers (PML), with a scattering boundary condition.

Field Quantities Extracted: Near-field $|E|^2$, scattering cross- section, and absorption spectra.

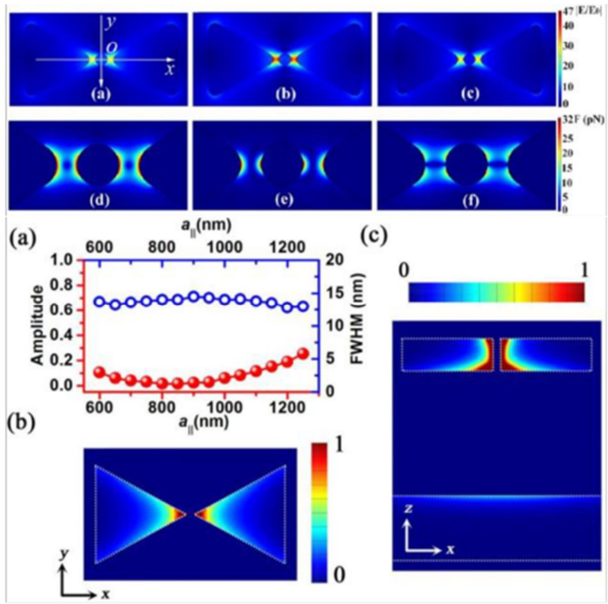
C. Fabrication

Nanostructures fabricated using Focused Ion Beam (FIB) milling on gold thin films, followed by selective functionalization change. This resulted in a shift in the resonant wavelength. The sensitivity obtained was between 200 and 400 nm/RIU. This value is consistent with other published reports. It is worth mentioning that the use of gold makes the nanoantenna stable for biosensing purposes but leads to some loss of optical energy, which broadens the resonance

IV. RESULTS AND DISCUSSION

A. Electric Field Distribution

It can be seen from the simulation results of the gold bowtie Nano-antenna in 3D mode that there is good localization of the electric field in the 10 nm gap area. There is one hotspot at the center of the antenna because of the good coupling of the two triangular tips. At the point where the gap occurs, the electric field strength is very high, but then diminishes rapidly.



B. Resonance and Field Enhancement

Resonance in this nanoantenna occurs between the visible light spectrum and the near-infrared range, which is from 650 nm to 800 nm. During the resonance process, the electric field is significantly amplified, with its magnitude ranging from 104 to 106. This increase in the field magnitudes is attributed mainly to the geometric structure and inter-tip gap spacing, which lead to an accumulation of charges at the tips of the antenna.

C. Sensing Performance and Discussion

The model showed that the nanoantenna has a high sensitivity to changes in the refractive index of its surroundings. When a molecule is placed close to the hotspot, the dielectric properties of the medium

V. CONCLUSION

This paper brings together existing research related to molecular sensing using optical nanoantennas. Improvements in areas such as plasmonic coupling and enhanced field scattering will make nano-antennas an important part of future biochemical sensors. In the future, the use of photothermal and quantum plasmonics will allow multiplexing capabilities in molecular diagnostics.

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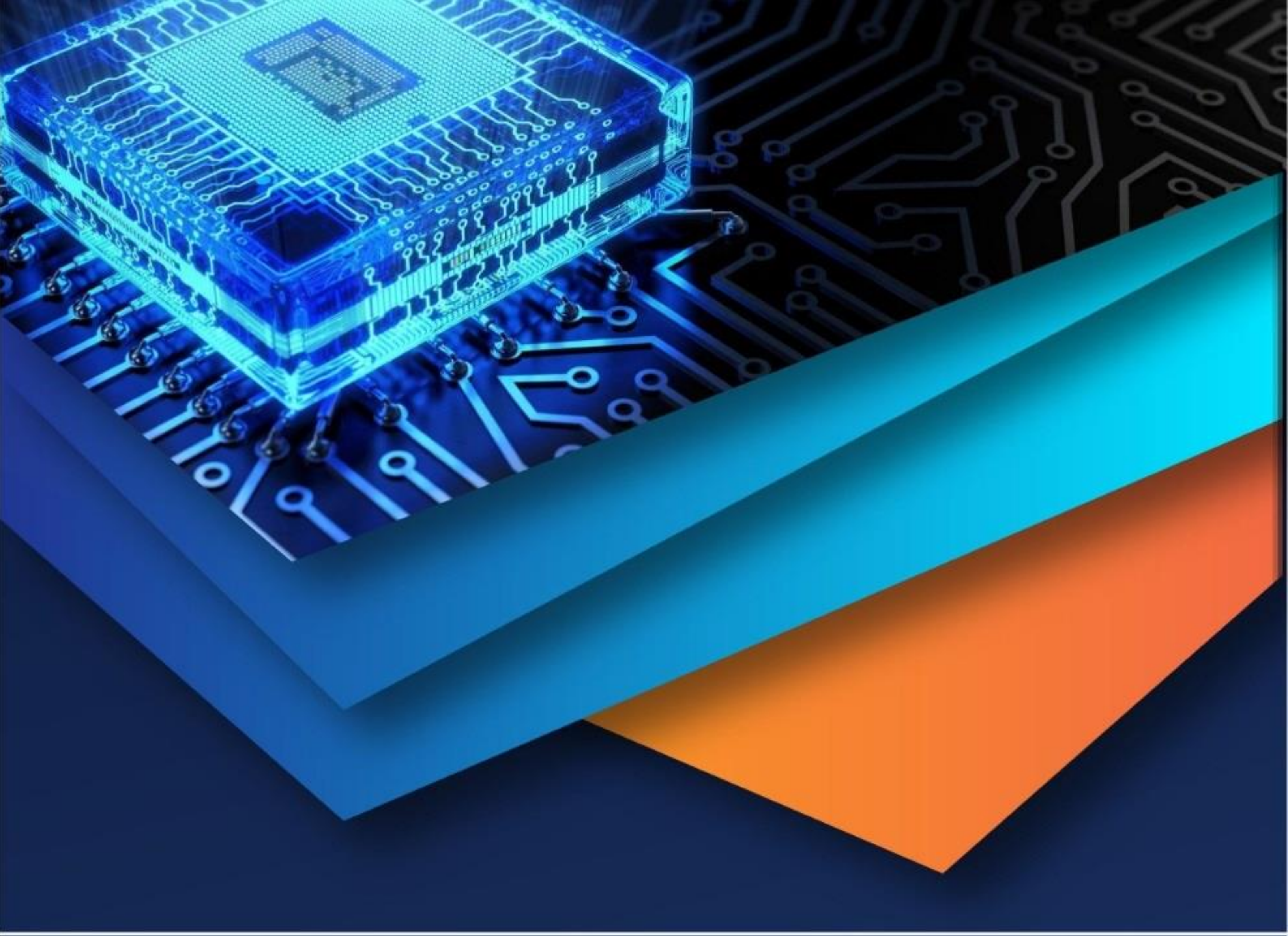

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