An Asymmetric Star Design for the Dynamic Control of Quantum-Emitter-Coupled Plasmonic Nanoantenna Emission

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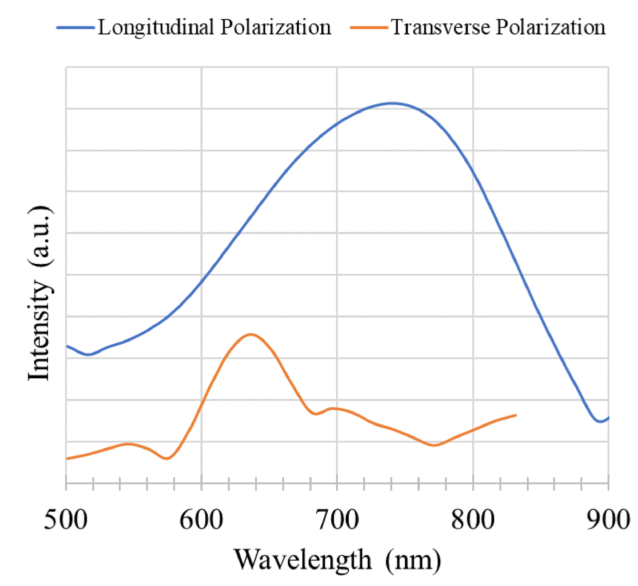
***Abstract*— Plasmonic single nanoantennas and meta-surfaces can both enhance and manipulate emission from potential quantum emitters while their layer-like nano thick structure renders them integrable into quantum and nano-devices. Here we proposed an Asymmetric Star Nanoantenna design, which when coupled to a single quantum dot emitter, offered unique resonant enhancements in both single and array arrangements. This enhancement was most established with the array, where 3 main polarization tunable behavioral states were identified, ones we described as two, one and steady mode patterns. This polarization driven functionality could offer a much-needed means of control over quantum emitters.**

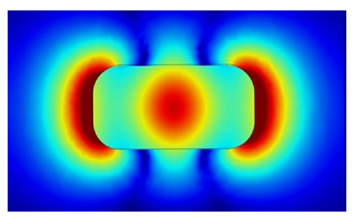
I. Materials and Methods

Obtaining scattered field intensity and changes made to typical setup

To investigate the coupling of the quantum dot (QD) excitation source, it was our goal to fully depend on **finite element analysis and simulation**. The QD was therefore modelled as an electric point dipole embedded in GaAs crystal substrate, while the resulting interaction was directly studied from a full field simulation. **COMSOL Multiphysics v5.3** was used to reproduce past experimentally verified results [3], [6]–[10] and yielded comparable shapes and frequency of resonance peaks, ranging from 650-850 nm.

The full field with the **antenna set to air** was evaluated, then another full field simulation followed with **antenna set to gold**. The response of gold was evaluated by taking the difference between maximum field values along each of X, Y and Z between the air and gold cases. The **norm of this resultant vector** would be taken to be **proportional to the scattered field intensity**





II. Nanoantenna Design

Unit cell (320 nm x 250 nm) Base:

- 100 nm thick GaAs base, $\varepsilon_r = 12$,
- GaAs base covered by a native 2 nm thick Ga2O3 layer, $\varepsilon_r = 4$.
- Top 3 nm thick Al2O3 layer, $\varepsilon_r = 3.14$.

Gold nanoantenna:

- underside padded by an adhesive oxidized chromium, $\varepsilon_r = 1.8$.
- Due to gold's unique ε_r around visible frequencies it was modelled with frequency dependent complex & real parts interpolated from Yakubovsky et al.'s database [11].
- Asymmetric 3 armed star design. Long-135, intermediate-70 and short 45 nm arms 25 nm wide.

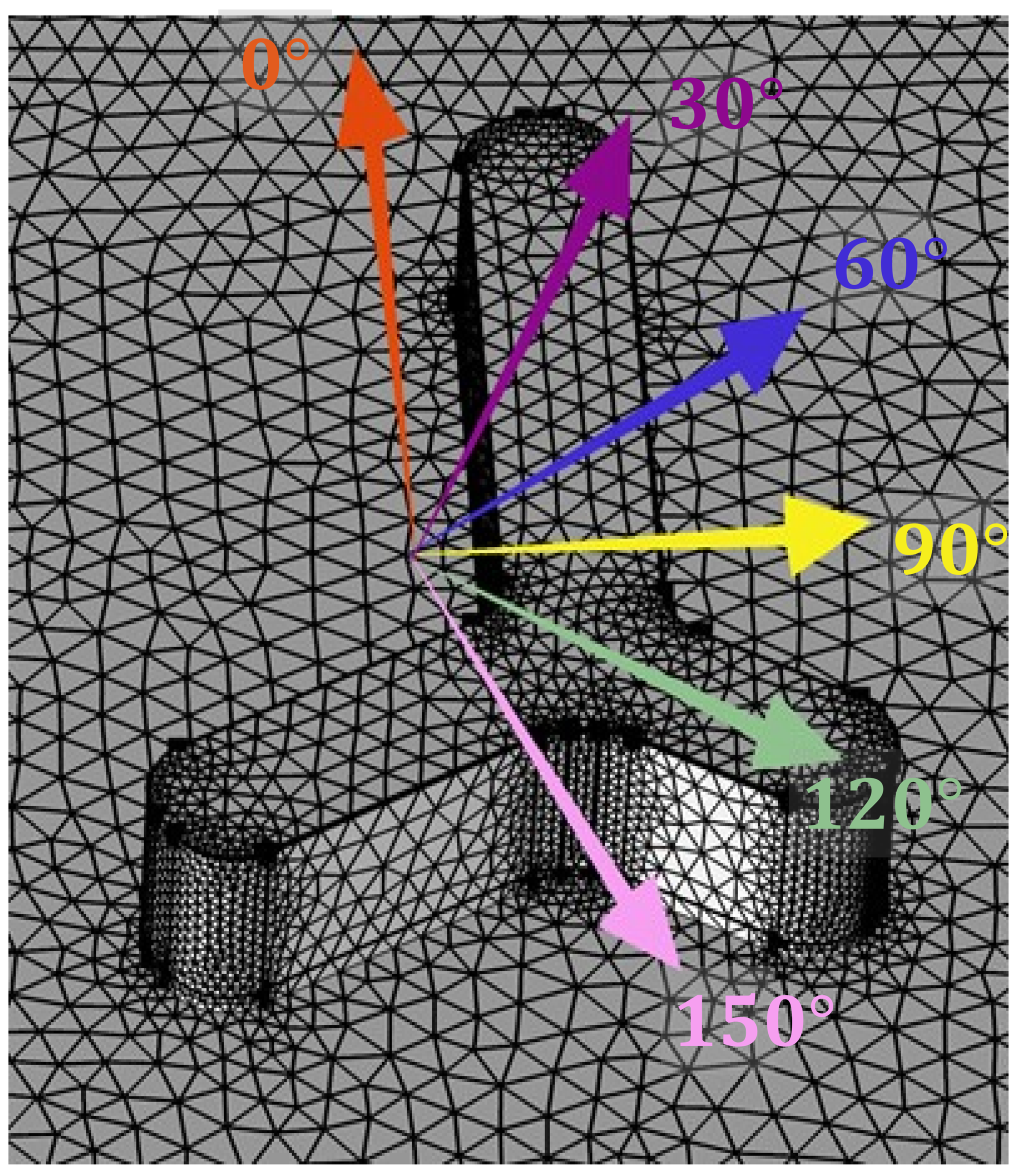


Figure 2. Extra fine mesh of the Asymmetric nanoantenna; 135 nm arm at 0°, 70 nm arm at 60°, 45 nm arm at 120°

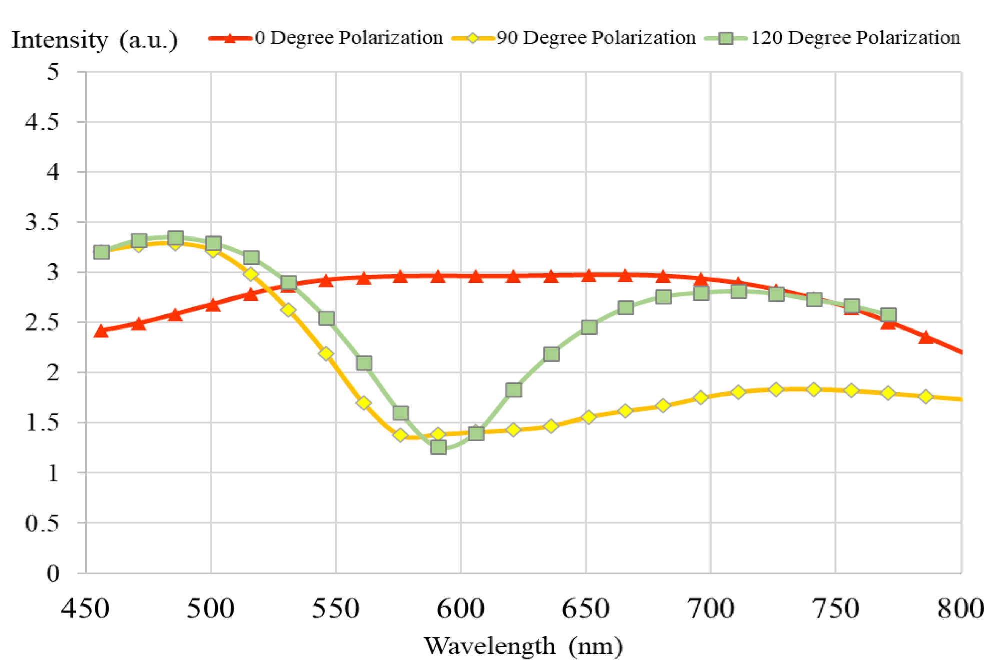


Figure 4. Three behavioral patters seen at 0, 90 and 120°

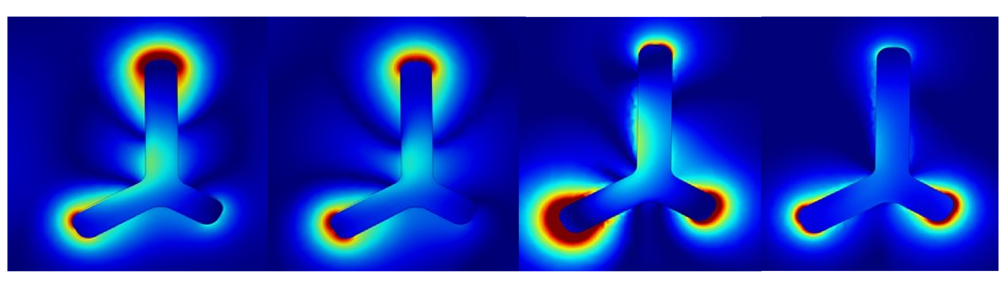
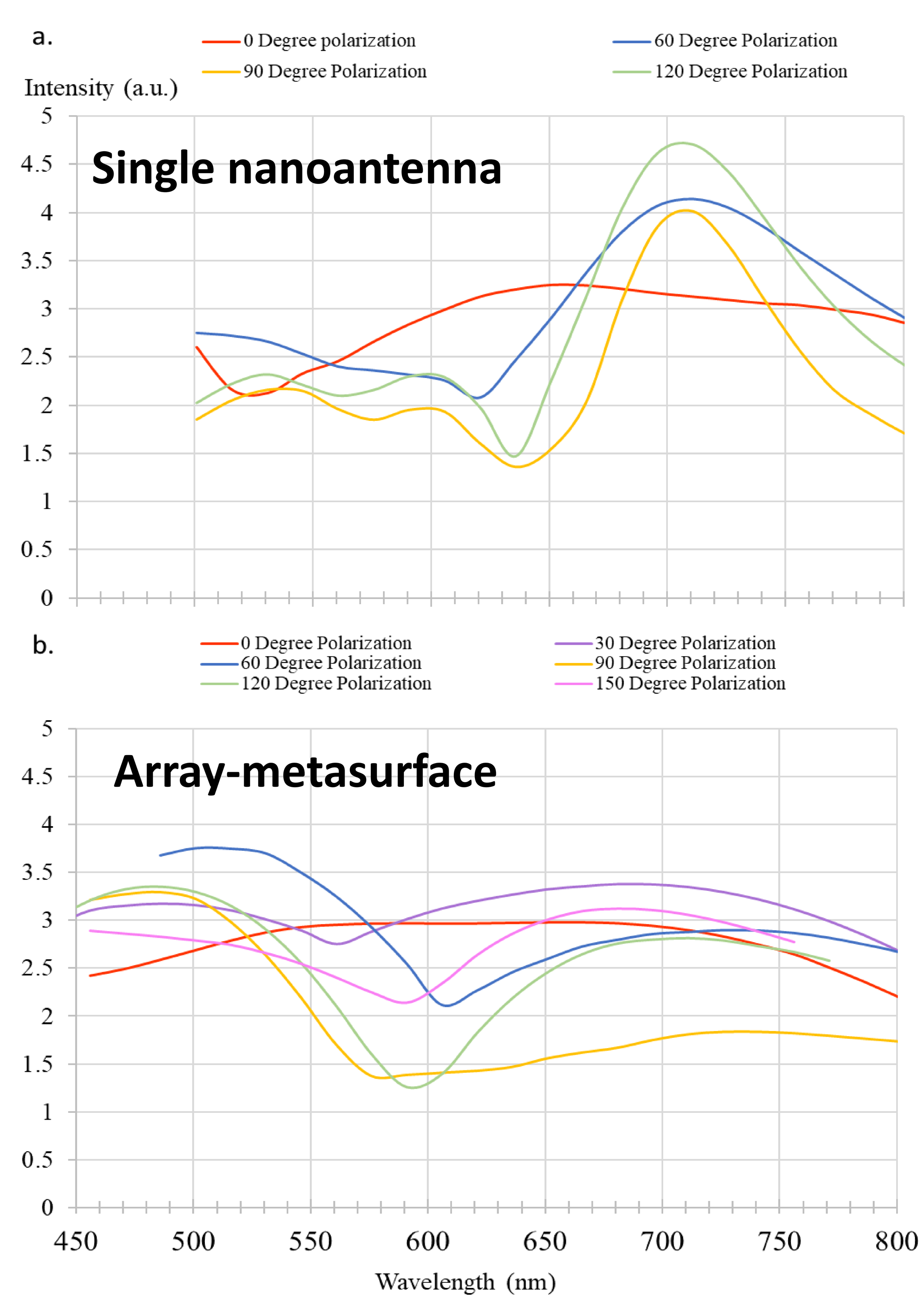


Figure 5. Response of a 0° polarized source around 550 nm **(a)** and 700 nm **(b)** showing a shift in emission from the long arm, to the left arm. **(c)** represents emission at peak frequency from a 90° source at 500 nm, and is a pattern 2 case, with 1 peak at 500 and a plateau of emission around 600-800 nm.. **(d)** shows the damping of emission at 800 nm.

III. Results and Discussion

Fig. 3a and 3b: Plots from parametric sweeps across the 450-800 wavelength range over 6 key polarization angles. for both **single cell** (a) and **array** arrangements (b) of nanoantennas.



For **single cells**, as in fig 3a., angles between 60 and 120°, saw **peaks at 711, 600 and 515 nm**, regardless of polarization angle. with **larger angles showing sharper and higher peaks**. Below 60°, most notably at 0°, widening effects were sufficient enough to force **peaks to coalesce** into an emission plateau of damped emission. For **arrays**, damping effects are more prominent. The **three peaks between 60° and 120 ° now show 2 clear wider peaks** around both the 700nm and 500 nm. At 90° we lose any effective peak through 550-800 nm, rather it gives a clear peak, comparable to the 120 below 580 nm.

IV. The three patterns

Pattern 1: "two peak mode" :

Peaks roughly around 700 and 500 nm. This Unlocks **two different excitation frequencies** at the 500 and 700 nm wavelength marks. This behavior is observed between **30 to 60 and 120 to 150°.** The pattern mimics two single rods at different modes.

Pattern 2: "one peak mode" :

Seen around **90° polarization**. It maintains the 500nm peak of pattern 1, with a matching intensity and spread, but dampens the 700 nm peak creating a near steady emission region between 580-800 nm

Pattern 3: "Steady mode" :

This pattern provides an **emission plateau at high intensity** around the visible region, then dies out.

V. In Conclusion :

we have demonstrated how the asymmetric star design, creates unique **dynamically tunable polarization dependent modes** that were unavailable to traditional shapes used in literature.

REFERENCES

[1] B. Liu, C. Tang, J. Chen, M. Zhu, M. Pei, and X. Zhu, "Electrically tunable fano resonance from the coupling between interband transition in monolayer graphene and magnetic dipole in metamaterials," *Sci. Rep.*, vol. 7. [2] V. Amendola, R. Pilot, M. Frasconi, O. M. Maragò, and M. A. Iatì, "Surface plasmon resonance in gold nanoparticles: A review," *J. Phys. Condens. Matter*, vol. 29, no. 20, 2017. [3] W. S. Chang *et al.*, "Tuning the acoustic frequency of a gold nanodisk through its adhesion layer," *Nat. Commun.*, vol. 6, no. May, pp. 1–8, 2015. [4] O. Scholder, "Fabrication , Simulation and Characterization of Tunable Plasmonic Nano Antennas .," Doctoral Theis, Dep. of Inform.Technol. Electrical Eng, ETH Zurich, 2014. [5] F. Monticone and A. Al, "Metamaterials and plasmonics : From nanoparticles to nanoantenna arrays , metasurfaces , and metamaterials ∗," *Chinese Phys. B*, vol. 23, no. 4, 2014. [6] M. Pfeiffer *et al.*, "Coupling a single solid-state quantum emitter to an array of resonant plasmonic antennas," *Sci. Rep.*, vol. 8, no. 1, pp. 6–11, 2018. [7] P. K. Ghosh, D. T. Debu, D. A. French, and J. B. Herzog, "Calculated thickness dependent plasmonic properties of gold nanobars in the visible to near-infrared light regime," *PLoS One*, 2017. [8] M. Pfeiffer *et al.*, "Eleven nanometer alignment precision of a plasmonic nanoantenna with a self-assembled GaAs quantum dot," *Nano Lett.*, vol. 14, no. 1, pp. 197–201, 2014. [9] A. G. Curto, "Unidirectional Emission of a Quantum Dot Coupled to a Nanoantenna Unidirectional Emission of a Quantum Dot Coupled to a Nanoantenna," *Science (80-.).*, vol. 329–5994, no. August, pp. 930–933, 2010. [10] A. M. Funston, C. Novo, T. J. Davis, and P. Mulvaney, "Plasmon coupling of gold nanorods at short distances and in different geometries," *Nano Lett.*,2009. [11] D. I. Yakubovsky, A. V. Arsenin, Y. V. Stebunov, D. Y. Fedyanin, and V. S. Volkov, "Optical constants and structural properties of thin gold films," *Opt. Express*, vol. 25, no. 21, p. 25574, 2017. [12] R. Carminati, M. Nieto-Vesperinas, and J.-J. Greffet, "Reciprocity of evanescent electromagnetic waves," *J. Opt. Soc. Am.* 1998.