

# Electro-tuneable nanoplasmonic Fabry–Perot cavity for smart nano-optical devices

Debabrata Sikdar<sup>1,2</sup> and Alexei A Kornyshev<sup>1</sup>

<sup>1</sup> Department of Chemistry, Imperial College London, South Kensington, London, SW7 2AZ, UK.

<sup>2</sup> Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati, Guwahati, 781039, India

Authors' e-mail addresses: [d.sikdar@imperial.ac.uk](mailto:d.sikdar@imperial.ac.uk), [deb.sikdar@iitg.ac.in](mailto:deb.sikdar@iitg.ac.in), [a.kornyshev@imperial.ac.uk](mailto:a.kornyshev@imperial.ac.uk)

**Abstract:** We propose and theoretically demonstrate a voltage-controlled nanoplasmonic Fabry–Perot cavity—formed between two parallel ‘mirror’-like reflective monolayers of metallic nanoparticles assembled at the interfaces of two parallel, transparent, polarized electrodes—enabling fast *in-situ* electro-tuning of optical transmission *via* manoeuvring inter-particle gap and plasmonic coupling without altering the cavity structure.

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## 1. Introduction

Tuneable Fabry–Perot (FP) cavities are promising candidates for developing numerous optical devices aimed at gas analysis, spectrometry, optical fiber sensing, bio-chemical sensing, and refractive index measurement, just to name a few [1–3]. Typically an FP cavity comprises two parallel reflective surfaces that allows sharp transmission peaks only at those wavelengths, which constructively interfere within the cavity length, of the light entering that cavity [2]. Recently, a few electrically adjustable FP cavities, comprising parallel reflector plates, are realized by deploying liquid crystals, silicon and organic–inorganic hybrid methods, *etc.* that allow electrical tuning of the transmittance spectrum [3, 4]. There are various other tuneable, micro-machined FP-cavity based systems, but mostly made from expensive, complicated top–down fabrication methods and usually demand large potentials for tuning [4].

Here, we propose an alternative, cost-effective, bottom–up design of a nanoplasmonic FP cavity based on directed voltage-controlled assembly/disassembly of charged metallic nanoparticles (NPs) on electrified electrodes, where the cavity properties are quickly alterable (even the cavity can be constructed/deconstructed *at will*) with ultra-low voltage variation and within millisecond timescale [3]. Our design comprises two parallel transparent electrodes in aqueous electrolyte solution, forming two polarizable solid–electrolyte interfaces (SEI) for voltage-directed assembly/disassembly of NPs capped with charged ligands. Dense monolayer of NPs on SEI enacts a mirror-like reflective surface, whose reflectivity spectrum can be tuned with inter-particle spacing. Under positive (negative) polarization of the electrodes, an FP cavity between two electrodes can be formed (deconstructed). Since intensity, wavelength, and linewidth of the reflection peak depend on the NP packing density, which can be tuned *via* applied potential, the transmission from our FP cavity can be electro-tuned *in-situ*, without need for mechanically changing the cavity length. Plasmonic NPs were also used by other researchers to enhance transmission from FP cavities, and optical tuning was achieved by deploying TiO<sub>2</sub> NP thin film coating, embedded Au NPs, and hybrid NP-cavities [4].

Here, we discuss the design and evaluate the performance of our unique nanoplasmonic FP cavity. Our theoretical framework, verified against full-wave simulations, provides design guidelines for such NP-based ‘smart’ FP cavity.

## 2. Proposed Structure and Theoretical Model

Figure 1 shows the schematic of our proposed electro-tuneable FP cavity comprising negatively-charged gold NPs in aqueous solution between two parallel 50 nm thick transparent indium tin oxide (ITO) electrodes. When the electrodes are negatively polarized, NPs remain dispersed in the solution and no FP cavity is formed [Fig. 1(a)]. With positive electrode polarization, NPs assemble on the two electrodes forming densely-packed arrays. By virtue of the strong surface plasmon resonance, an assembled monolayer of NPs on each ITO electrode reflects light like a mirror [5], where the NP packing density increases with applied electrode potential [*cf.* Figs. 1(b).i-ii]. Thus an FP-cavity is formed in between two assembled monolayers, whose reflectance properties are easily tuneable by changing inter-particle coupling *via* simply adjusting the positive polarisation of the electrodes, while leaving other physical parameters of the system unchanged. Using our quasi-static effective medium theory (EMT) we first model the assembled NP monolayers as uniform pseudo NP-films [Fig. 1(c)]. The longitudinal and transverse components of the permittivity of those NP-films are given by [5]

$$\epsilon_{\text{NP-film}}^{\parallel}(\omega) = \epsilon_s + \frac{8\pi}{\sqrt{3}a^2d} \beta_{\parallel}(\omega); \quad \frac{1}{\epsilon_{\text{NP-film}}^{\perp}(\omega)} = \frac{1}{\epsilon_s} + \frac{1}{\epsilon_s^2} \frac{8\pi}{\sqrt{3}a^2d} \beta_{\perp}(\omega), \quad (1)$$

where NPs of radius  $R$ , with inter-NP gap  $g$  are assumed to form an hexagonal close packed array. Here,  $d = 4\pi R^3/3a^2$  is the thickness of the pseudo-film;  $a = 2R + g$  is the NP-lattice constant;  $\epsilon_s$  is the permittivity of the surrounding medium (here, water in all calculations) and  $\beta_{\parallel,\perp}(\omega)$  are the effective quasi-static dipolar polarizabilities of each NP in the pseudo-film. With the knowledge of permittivity of each layer in the FP cavity we can deploy multi-layer Fresnel scheme (MLFS) [2] to calculate the transmittance spectra based on our EMT-MLFS approach [5].

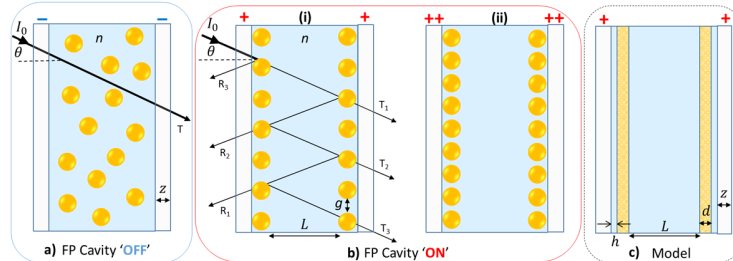


Fig. 1. Proposed FP Cavity: (a) With negative electrode polarisation, NPs remain dispersed in the bulk and no FP cavity is formed. (b) With positive electrode polarisation, NPs assemble along the ITO-water interface in densely packed arrays [case (i) to (ii)] to form an FP-cavity of length  $L$ . (c) EMT model consisting two pseudo-films of NPs of thickness  $d$  along ITO electrodes of thickness  $z$  with a spacer of height  $h$ .

### 3. Results and Discussion

Transmittance from an absorbing FP cavity can be estimated as  $T_{A \neq 0} = \frac{1}{1+F \sin^2(\delta/2)} K^2$ , where  $K = (1-A-r^2)/(1-r^2)$ ,  $F = 4r^2/(1-r^2)^2$  is the coefficient of finesse,  $r$  is the reflection coefficient and  $A$  is the absorbance of each monolayer of NPs, and the round-trip phase difference between each adjacent transmitted wave is  $\delta_{A \neq 0} = \frac{4\pi n L \cos \theta}{\lambda} - 2\arg(r)$  with  $n$  denoting the refractive index of the cavity medium and  $\theta$  denoting the incident angle [Fig. 1]. By obtaining  $r$  based on EMT, the transmittance calculated from the classical FP theory can be compared against our EMT-MLFS estimation of the full system [Fig. 2(a)]. For a given wavelength, Fig 2(b) shows change in transmission intensity, linewidth and finesse with inter-NP spacing  $g$ . Figure 2(c) compares our EMT-MLFS against full-wave simulations, showing that theory approximates simulation results better at larger  $g$ . The transmission spectra [Fig. 2(d)] simulated for various inter-NP spacing evidence the possibility of *in-situ* tuning in such FP cavity, which can be done practically by finely adjusting the electrode polarity. Note that, in this work we considered  $\theta = 0^\circ$ ,  $L = 1000$  nm, and  $h = 2$  nm.

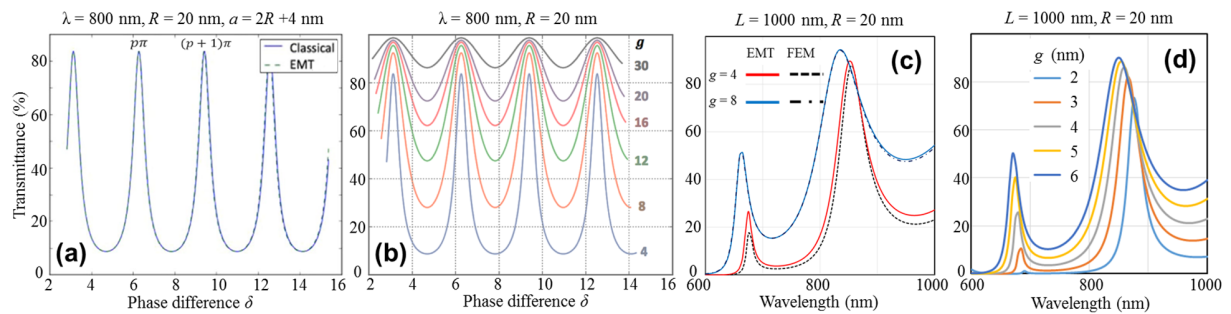


Fig. 2. (a) A plot of transmittance versus the phase difference  $\delta$  comparing classical FP theory and EMT-MLFS. (b) EMT-MLFS calculations of transmittance against the phase shift  $\delta$  at different inter-NP spacing  $g$ . (c) Comparison between EMT-MLFS and full-wave finite element method (FEM) simulations. (d) Tuneability of transmittance spectrum with inter-NP spacing, to be induced by change in electrode polarity.

### 4. Conclusion

Our design shows that without altering the length of a nanoplasmonic FP cavity, its transmission properties can be electro-tuned *in-situ* by changing the inter-NP separation. This ‘bottom-up’ approach offers benefits such as ease of fabrication and programmability of the optical responses, paving ways for novel electro-tuneable optical devices.

### 4. References

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