Opto-electromagnetic Responses of Tamm Plasmon Polariton Modes in a Symbiotic Dual-Metallic architecture

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Abstract

We report a Tamm plasmon polariton (TPP) arrangement whose design consists of a thin Silver (Ag) film which is the plasmon-active metal and lies adjacent to the distributed Bragg Reflector (DBR) structure. The DBR consists of periodically stratified layers of Ta_2O_5 and SiO_2. TPP modes are excited through normal incidence using a white light source and we have obtained the corresponding reflectivity spectrum as a function of wavelength. The excitation spectrum is characterized by a sharp and distinguishable reflectivity dip within the photonic band-gap of DBR. Extending this version of the idea, we have replaced the single plasmon-active metal by two metals to overrule the drawbacks of these single metals concerning their physiochemical properties like propagation length, chemical stability, and various losses during propagation of the plasmon wave, etc. Hence, we have obtained the reflectivity characteristics for different bimetallic architecture supporting TPP resonances. Thereafter, we have also obtained the Full Width at Half Minimum (FWHM) wavelengths and Quality Factor (Q-Factor) characteristics as a function of metal thickness for two different plasmon active metallic combinations, where the total bimetallic thickness remains constant. The shortcomings of a particular metal are nullified by the presence of the other metal with it. Such an arrangement is envisioned for the fabrication of nanoscale smart devices like optical and biosensors having potential applications in social welfare domain like monitoring the levels of food adulteration and food safety, etc.

Keywords: *Tamm Plasmon, distributed Bragg Reflector (DBR), Reflectivity Spectrum, Dual-metallo-dielectric architecture, Quality Factor (Q-Factor)*

1. Introduction

A surface plasmon polariton (SPP) is an electromagnetic excitation formed at the interface of a metal and a dielectric material in response to externally applied electromagnetic fields [1]. They result due to surface charge density oscillations or surface restricted electron gas (plasma) oscillations and they are treated classically as particular solutions of Maxwell's electromagnetic wave equations under certain boundary conditions [1,2]. It is noteworthy here that in the limit of optical frequencies, the plasmon waves, are well characterized by a distinctive resonance frequency that arises due to metal-nanostructure interactions [3].

This surface plasmon resonance (SPR) based technology have achieved ground-breaking achievements in terms of device modelling like optical sensors, food adulteration detection sensors, modelling and fabrication of optoelectronic devices, light localization and control over nanoscales and many more experimentally reliable and smart applications [4,5]. The dispersion curve for the SPP exhibits parabolic nature which lies outside the light cone and the propagation vector exceeds to that of light in vacuum and therefore it cannot be excited directly through optical means [6]. As a consequence, it is required to deploy additional optical components like high refractive index prisms and Bragg-grating couplers to ensure wave vector matching and effective SPP excitations [6-8]. But this is not always a very convenient approach in real experimental problems and this excitation scheme remains a challenge in terms of phase matching for monolithic integration of photonic devices and circuits.

In order to address this concern, recently, a novel version of this surface plasmon polariton known as Tamm plasmon polariton has been proposed which are formed at the interface of a plasmon active metal and a distributed Bragg Reflector (DBR) [6-8]. DBR is a periodic arrangement of two dielectric media, having layered sheets of optical thickness near about half wavelength of light. Unlike SPP, Tamm plasmon polariton are typified by a zero or null in-phase wave vector and hence they can be directly optically excited [9]. These TPP modes exhibit distinguishable resonances in their reflection spectra within the photonic bandgap, typically dictated by structural parameters, viz. thickness of the metal, the manifold of DBR layers and the nature of the constituents of metal and DBR [10].

It is an interesting matter of fact that unlike surface plasmon polaritons, Tamm plasmon polariton modes can exhibit both transverse electric (TE) and transverse magnetic (TM) mode of polarization at the metal-DBR interface for both normal and oblique incidence of light.

It is to be also noted here that the reflection coefficients can also be preferably determined by the optical transfer matrix method for a multilayered nanoscale architecture [11,12].

2. Experimental modelling

2.1 The monometallic-DBR geometry

The essential arrangement of typical metal-DBR geometry is shown in Fig. 1, where a pair of dielectrics are arranged periodically above a plasmon active metal. The thickness of the individual dielectrics in the given DBR structure is primarily dictated by the quarter wave condition, i.e.,

$$d = \frac{\lambda_{central}}{4n} \quad (1)$$

where, d is the width of the periodically repeating dielectric structures deposited above the metal surface, n is the refractive index of the chosen dielectric material. Here we have chosen Tantalum pentoxide (Ta_2O_5) and Silicon dioxide (SiO_2) as the dielectric components. The central wavelength has been assigned a value of 520 nm and the using the relations mentioned above, the results for the thickness of Ta_2O_5 and SiO_2 dielectric layers are 60 nm 88 nm respectively (d_1=66 nm & d_2=88 nm) and the photonic band-gap (PBG) lies in the visible region.

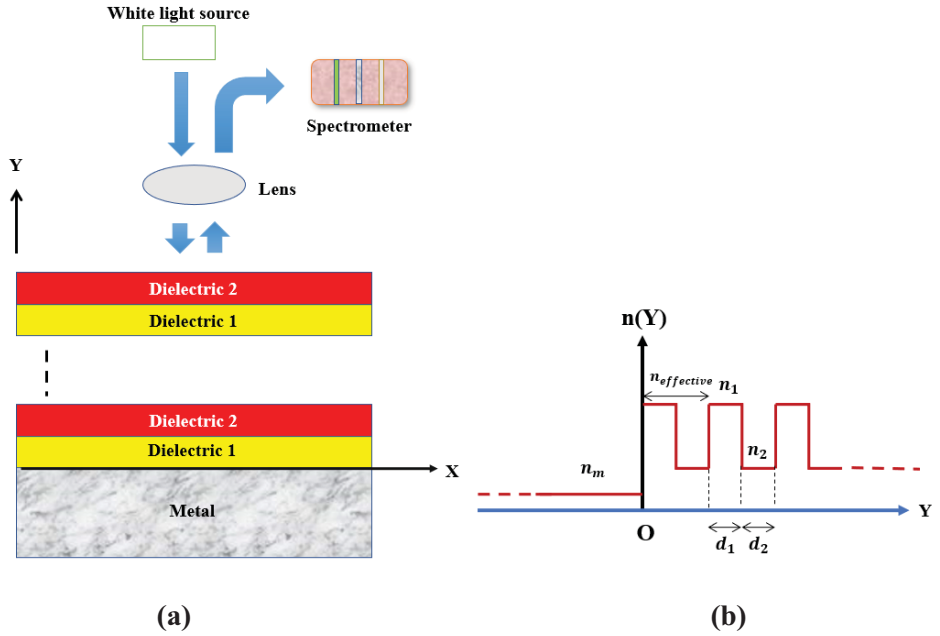

Fig 1. (a) Schematic diagram representing the TPP geometry consisting of metal and DBR. (b) Refractive index profile (RIP) corresponding to the geometrical arrangement of Fig 1(a)

2.2 Reflectivity spectrum for noble metals: Silver (Ag) & Aluminium (Al)

In our study, we have considered a broadband white light source from which an unpolarized beam is incident normally from air to the "metal-DBR" structure (see Fig 1. (a)) so as to get the reflection spectrum for different combinations of metal and the Bragg reflector. Here, the transfer-matrix method for normal incidence is being used to get the reflection spectrum characteristics. The simulated reflectivity characteristics of the different noble metals as a plasmon-active metal used in the metal-dielectric architecture as a function of wavelength are depicted in the following figures (Fig 2. (a) and Fig 2. (b)).

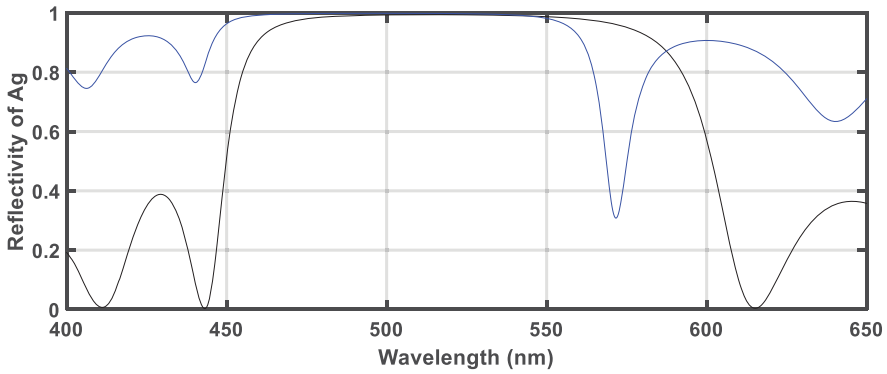

Fig 2. (a) The Reflectivity characteristics of Silver (Ag) for a thickness of 30 nm (blue curve) within the PBG (black curve).

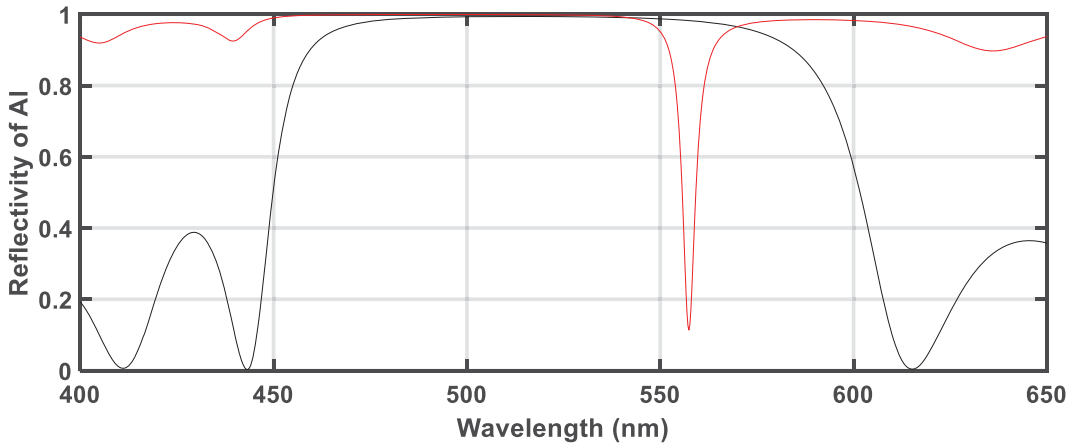

Fig 2. (b) The Reflectivity characteristics of Aluminium (Al) for a thickness of 30 nm (red curve) within the PBG (black curve).

It is to be noted from the previous two figures (see Fig 2.(a) & 2.(b)) that the black line touching wavelength axis at both points represent the photonic band-gap (PBG) or the bandwidth. Thus, from the two consecutive variations it is clear that the sharpness of reflection minimum is different for the two different metals, indicating that it is a function of the property of the metal. The sharp reflectivity minimum is basically a consequence of the excitation of a localized degenerate Tamm plasmon polariton mode which is confined at the metal-Bragg Reflector interface. Moreover, the arrangement using a single metal is advantageous in the sense that phase-matching wavelength can be varied over a wide spectral range by their sensible selection.

2.3 Optical Tamm states & reflectivity spectrum for a bimetallic arrangement of noble metals

In spite of the apparent success of using a monometallic configuration in the formation of Tamm plasmon polaritons and paving its way to a number of technological applications and usages, this configuration of TPP formation is often associated with a number of drawbacks. The drawbacks are essentially material-dependent, i.e., they are caused by the innate physical and chemical properties of the constituent metal. For instance, although Au is chemically stable, but it manifests clearly a high propagation loss due to its high absorption co-efficient, and hence limits the performance of the sensing device. Secondly, Ag, which in spite of the fact that it is associated lower propagation loss, it is vulnerable to oxidation effect, which subsequently worsens the device's performance. Lastly, Al has poor chemical stability to be used as reliable sensing device, though it has lower coefficients of propagation loss, exhibit super-large dispersive group velocities, extremely narrow bandwidth and highly economical.

In order to address these shortcomings in the fabrication of the device, we have extended our theoretical design one step ahead of our previous proposition, and replaced the single metal by a combination of two different metals having different physical and chemical properties. This bimetallic arrangement manifests an

act of artificial commensalism in terms of their key features. For instance, the bimetallic combination of Au with Al, addresses the poor chemical stability of Al and this combination can be used for sensing purposes with an appreciable theoretical estimate. In the light of the above discussion, we would like to show some results we have obtained through simulations using the Transfer-Matrix method. Those results are shown in the Fig 3.

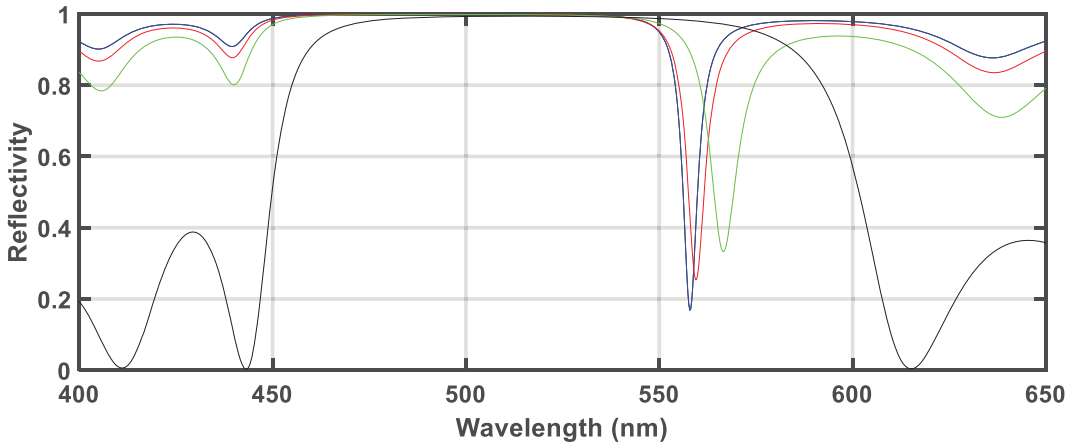

Fig 3. Simulated Reflectivity curve for the combination of Al and Ag of varying thickness (Ag being the closest metal to the analyte) where the total bimetallic is constant value of 30 nm (blue, red and green curve) within the PBG (black curve).

The figure (Fig 3.) shows the reflectivity spectrum for the pair of metals (Al & Ag) where Al lies above Ag. The variation in the spectrum is caused due to the change in thickness of the constituent metals, where the total metallic thickness is a constant, i.e., 30 nm. The black line touching the two points on the wavelength axis determines the photonic band-gap (PBG). Here Silver (Ag) is preferred over Gold (Au) because it has a better signal-to-noise-ratio (SNR) and superior in terms of its detection accuracy (DA) which is attributed to a wide range of applications like optical and electromagnetic sensing. The FWHM wavelengths and Q-Factor characteristics as a function of metallic thickness for the given pair of metals, i.e., Ag and Al are shown in Fig 4. (a) and Fig 4. (b) which estimates the efficiency of the photonic device to be used as a convenient and reliable photonic device.

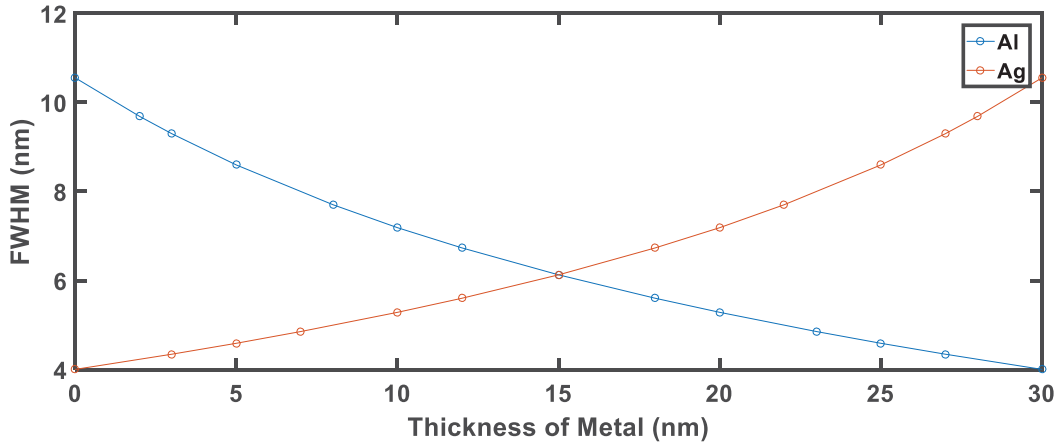

Fig 4. (a) The variation of FWHM wavelength with thickness of metals (for Al above Ag)

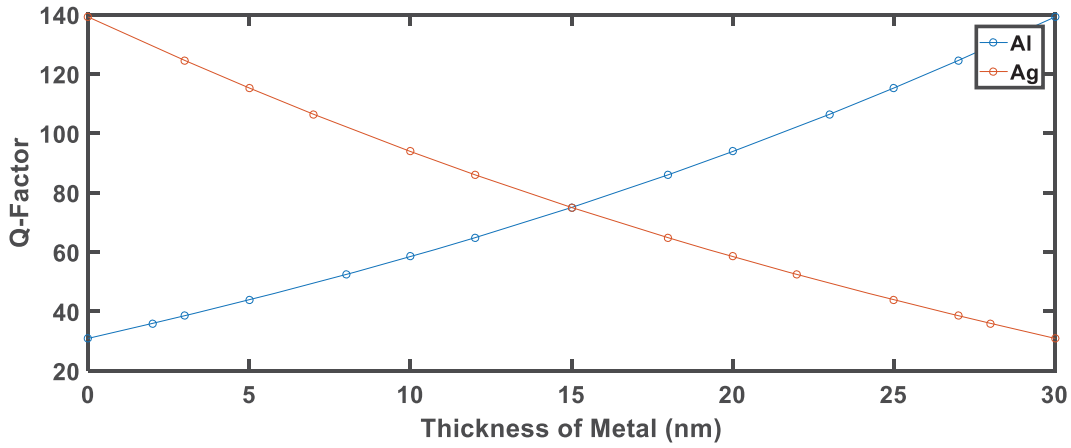

Fig 4. (b) The variation of Q-Factor with thickness of metals (for Al above Ag)

The Full width at half minimum (FWHM) wavelength characteristics and the Q-Factor are keynote parameters to be considered when it comes to the study of opto-electromagnetic properties. A higher value of the Q-Factor implies a longer time period of TPP mode before it decays away into the surrounding environment. Therefor the Q-factor is one of the key factors that dictate the dynamics of the photonic device in interest. The Q-factor of an opto-electronic device is mathematically described as follows.

$$\text{Q-factor (Q)} = \frac{\text{Resonant Wavelength } (\lambda_0)}{\text{FWHM Wavelength}} \tag{2}$$

The Q-factor is inversely dependent on the FWHM bandwidth. So, a lower value of FWHM indicates a higher Q-factor. The Q value is crucial for designing sensors with a good signal-to-noise ratio (SNR), oscillators exhibiting a low phase noise, and optical filter circuits with large noise rejection, stability and

higher gain. From the FIG 4(b), it is evident that Q-factor varies proportionally with the thickness of Al, whereas, it decreases upon increasing the thickness of Ag that is quite agreeable with the FWHM characteristics. So, it is essential to choose the individual metallic thicknesses in order to ensure a maximization of the measure of the Q-factor for fabrication of smart and efficient nanophotonic gadgets.

3 Conclusion

In a nutshell, we studied the reflection spectrum for conventional-mode TPP and obtained the reflectivity characteristics by replacing a single plasmon-active metal by two plasmon-active metals. It basically eliminates the drawbacks of the single metals with regard to their individual physical and chemical properties like chemical stability, propagation length and losses, tendency of oxidation, etc. Furthermore, we theoretically presented an idea to enhance the sensing features of TPP modes by studying the reflectivity characteristics of Silver & Aluminium, both in their monometallic and bimetallic configurations, their FWHM wavelengths and Q-Factor characteristics. The Q value varies from a range of 30.93 to 139.2 with the increase in the thickness of the Aluminum from zero nm to 30 nm and decrease in the thickness of Silver accordingly keeping the total bimetallic thickness constant. Thus, to ensure a higher efficiency, it is required to maximize the thickness of Aluminium. This bimetallic configuration is theoretically expected to impact the device's potential in terms of sensing and remains a talking point in our future scope of research. The suggested scheme can be potentially employed to areas of biosensing involving integrated nano-fluidic channels.

4 Acknowledgement

We would like to thank Amity University, Kolkata whose support regarding the execution of this research work has been a milestone in the sincere execution of this project.

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