Controllable Tamm Plasmon Effect Designed by Admittance Loci

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Abstract – Tamm plasmon is a plasmonic resonance happens at the boundary of photonic crystal and metal. In this work, a novel design tool based on admittance loci is proposed to demonstrate the relationship between Tamm plasmon structure and the corresponding resonance effect. The tunability of resonance wavelengths and the optimization of coupling efficiency are presented.

I. INTRODUCTION

Tamm plasmon (TP), a plasmon state excited at the interface between a Bragg mirror (BM) and metal film, has gathered great attention for the past few years. For a standard quarter-wavelength BM, the Tamm plasmon resonance wavelength($\lambda_{TP}$) is within the optical band gap, and can be roughly described as equation 1 [1].

$$\lambda_{TP} = \lambda_0 + \eta \lambda_{plasma}$$  (1)

Where $\eta$ is described in equation 2.

$$\eta = 2 \left| \frac{n_H - n_L}{\pi \sqrt{\varepsilon_B}} \right|$$  (2)

Where $n_H$ and $n_L$ are the refractive indices of the BM layers, $\lambda_0$ is the central wavelength of BM, $\varepsilon_B$ and $\lambda_{plasma}$ stand for background dielectric constant and plasma wavelength of the metal, respectively. Several literatures have reported on tuning TP response by varying the thickness of metal film or the BM layer that is adjacent to the metal [2]. However, none of the studies provide a comprehensive way to design the TP resonance effect. In this article, we proposed using the admittance loci to analyze and further design the TP resonance. First, a 28 layers BM with $\lambda_0 = 1300$ nm comprised of GaAs and AlAs where refractive indices are 3.7 and 3.0 respectively is applied [3]. Then, a 30 nm Au thin film is placed on top of the BM as the schematic figure shown in Fig. 1. Second, an unambiguous approach of tuning TP response including $\lambda_{TP}$ and the coupling efficiency at $\lambda_{TP}$ is performed based on observation and analysis of admittance loci, where admittance loci are the plot of effective admittance from substrate to the top of the structure.

II. SIMULATION RESULT

A transfer matrix method shown in equation 3 is applied to calculate the reflectance spectrum and admittance loci of using TP structure.
\[
\begin{bmatrix}
E_a \\
H_a \\
E_b \\
H_b
\end{bmatrix} = \begin{bmatrix}
\cos\delta & i\sin\delta/\eta \\
i\eta\sin\delta & \cos\delta
\end{bmatrix}
\begin{bmatrix}
E_a \\
H_a \\
E_b \\
H_b
\end{bmatrix}
\]

(3)

Where \(E_a\) and \(E_b\) are the tangential components of electric field at top and bottom boundary of a layer, while \(H_a\) and \(H_b\) are for the magnetic field; \(\eta\) is the admittance of the layer; \(\delta\) is the optical path length in the layer.

A. Layer Design for Enhancing TP Resonance

For the structure shown in Fig. 1, \(\lambda_{TP}\) is found at the wavelength which is 66 nm longer than \(\lambda_0\) when incident light comes from metal side. The admittance loci calculated at such wavelength explain the phenomena. Although the effective admittance of BM is away from incident medium, which is air in our calculation, the metal layer’s admittance loci make the total effective admittance close to it, leading to the drop in reflectance spectrum. However, in admittance loci, we notice that the reflectance drop of this effect can be further improved by just slightly modifying the layer thickness. Reducing the layer thickness of gold layer from 30 nm to 19 nm, and top most layer of BM from 87.8 nm to 81.8 nm could shift the admittance close to incident medium thus the input energy could have better coupling to TP resonance, which makes reflectance equals to zero. The corresponding reflectance spectrum is the black line shown in Fig. 2(b)

The admittance loci of the TP structure are shown in Fig. 2 (a). The close circles indicate the interface for the top dielectric layer and metal layer, while the asterisk indicates the gold/air interface. The purple ellipses are isoreflection curve for every 5%.

Fig. 2. (a) The admittance loci for light incident from front (Au thin film) side. The purple ellipses are isoreflection curves for every 5%. The solid line and dot line represent structures before and after optimized, respectively. (b) Reflectance spectrum for bare BM and TP structure with/without optimization. The inner figure shows how light source incident in this case.

Base on the technique of using admittance loci, the difference of excitation of TP resonance from the metal side or BM side is also been studied. A similar enhancement approach can be applied when light incidents from the BM side as shown in Fig. 3.

Fig. 3. Reflectance spectrum for TP structure with/without optimization. The inner figure shows how light source incident in this case.

By the observation of admittance loci, a revising approach of reducing the number of BM layers from 28 to 20 is applied in this case, making the effective admittance close to incident medium. An enhancement of reflectance...
drop can be easily observed in Fig. 3 after reducing the layer number. Coupling efficiency enhancement judging by $\Delta R_{\text{enhance}}$ divided by $\Delta R_{\text{origin}}$ where $\Delta R = 1 - R_{\text{resonance}}$ are 1.23 and 1.64 for light incident from metal side and BM side, respectively.

B. Tuning Tamm Plasmon Wavelength ($\lambda_{TP}$)

Not only $\Delta R$ but also $\lambda_{TP}$ is highly related to the variation of top most BM layer and metallic layer. Admittance loci can also be used to shift $\lambda_{TP}$. All $\lambda_{TP}$ shown in previous case is longer than $\lambda_0$. Now, by observation of admittance loci, two ways to shift $\lambda_{TP}$ to wavelength shorter than $\lambda_0$ are easily predicted.

First, if top most layer of BM is changed from high refractive index layer (H) to low refractive index layer (L), $\lambda_{TP}$ can be shifted to shorter wavelength. Fig. 4(a) shows when a 130 nm L layer is added on top of the BM, $\lambda_{TP}$ is shifted to 1210 nm. Second, if the thickness of top H layer in BM is greatly increased, $\lambda_{TP}$ can also be shifted to shorter wavelength. Fig. 4(b) shows when the thickness of top H layer is increased by 130 nm, $\lambda_{TP}$ could be shifted to 1250 nm. Base on this technique, TP could be easily tuned to any wavelength where it is needed, which would be very helpful for the design in the application like a notch filter in visible or NIR.

![Fig. 4. (a) $\lambda_{TP}$ is shifted to 1210 nm when an extra 130 nm L is added on top of BM. (b) $\lambda_{TP}$ is shifted to 1250 nm when top most H is extended by 130 nm.](image)

III. CONCLUSION

In this work, a useful technique to tune the TP response, including coupling efficiency at $\lambda_{TP}$ and shifting of $\lambda_{TP}$ based on analysis and observation of the admittance loci has been proposed. Coupling efficiency of TP resonance is successfully enhanced by 1.23 and 1.64 times for the incidence from metal side and BM side, respectively. Also, $\lambda_{TP}$ could be precisely tuned to any wavelength within the photonic band-gap. The small FWHM of TP resonance and near-field enhancement could be further used to vertical-cavity surface-emitting laser (VCSEL) or notch filter application.

IV. ACKNOWLEDGEMENT

This work is supported by the National Science Council, Taiwan, ROC (No. 102-2218E-009-004).

V. REFERENCES

