

Efficient Excitation of Leaky Surface Plasmon Polaritons in Stripe-based Structures Using the Kretschmann Configuration

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 6 January 2022 Received in revised form 23 February 2022 Accepted 28 March 2022 Available online 29 March 2022</p>	<p>The growing interest in surface plasmon-based technologies has been driven by their promising applications in nanoparticle trapping, biosensing, and real-time in-situ diagnostics. Among these, <i>leaky surface plasmon polaritons (SPPs)</i> excited via the Kretschmann configuration on thin metallic films particularly gold have garnered significant attention due to their enhanced field confinement and propagation capabilities. In this study, we propose a novel approach to improving photon–plasmon coupling efficiency by utilizing a <i>tapered gold stripe</i> structure. The tapered geometry is designed to gradually concentrate SPPs toward the narrow end of the stripe, thereby significantly enhancing local field intensity. To investigate the behavior of SPPs under various excitation and tapering conditions, a three-dimensional finite-difference time-domain (3D-FDTD) simulation framework is employed. The results reveal that a tapering angle of approximately 45° yields a more than 60% increase in mode intensity after an 8 μm propagation distance, compared to a uniform (untapered) stripe. This improvement is achieved without significantly increasing power consumption, making the design highly energy-efficient. Furthermore, the proposed structure is readily compatible with low-cost microfabrication techniques, enabling straightforward integration into <i>lab-on-a-chip</i> and <i>optical manipulation</i> platforms. Overall, this enhanced tapered stripe design presents a promising avenue for advancing plasmonic optophoresis systems and may serve as a foundational element in the development of compact, integrated photonic chips for biomedical and nanoscale applications.</p>
<p>Keywords: Surface Plasmons, Gold Stripe, Kretschmann Configuration, FDTD Method</p>	

1. INTRODUCTION

Surface plasmon polaritons (SPPs), collective oscillations of free electrons in metallic films such as gold, aluminium, and silver coupled with electromagnetic fields, have garnered significant attention in recent years. This attention is attributed to their capability to guide electromagnetic energy below the diffraction limitation, presenting promising applications across physics, optics, chemistry, and medical sciences.

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Among the three surface plasmon polariton coupling methods namely Kretschmann, grating, and waveguide coupling [1,2] the Kretschmann configuration stands out as the simplest yet versatile, finding extensive applications. A particularly noteworthy platform for guiding excited surface plasmon polaritons, extensively explored in current studies, involves a thin gold stripe patterned on top of a glass substrate. This uncomplicated structure not only guides bound surface plasmon polariton modes but also supports the leaky surface plasmon polaritons mode [3], a mode with advantageous properties.

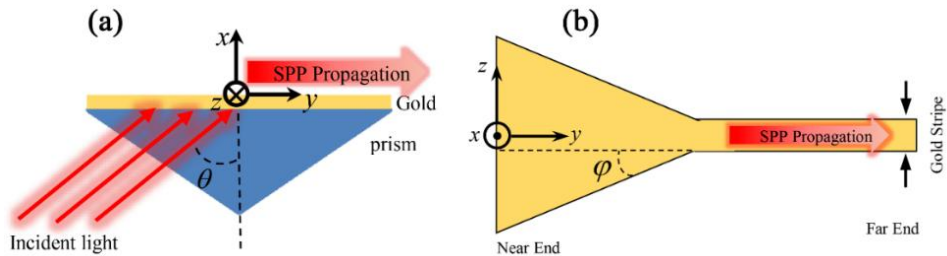


Fig. 1. (a) The Kretschmann configuration (side view), (b) structure of the tapered stripe (top view).

In the pursuit of advancing multifunctional Optophoresis systems designed for trapping and sensing micro- and nano-particles [4-6], this paper demonstrates a novel approach. We illustrate that by tapering the near end of a gold stripe, the excited surface plasmon polaritons can be effectively focused as they propagate along the stripe. This phenomenon results in the enhancement of leaky surface plasmon modes, thereby contributing to the overall efficacy of the system.

2. LITERATURE REVIEW

The Kretschmann configuration has been explored for efficient excitation of surface plasmon polaritons (SPPs) in various ways. Palomba (2008) demonstrated nonlinear excitation of SPPs using four-wave mixing, with a characteristic plasmon dip at the Kretschmann angle [7]. Vinogradov (2017) challenged the common belief that a plane wave incident at an angle greater than the angle of total internal reflection does not excite SPPs, showing that a narrow beam of infinite plane waves can indeed excite them [8]. Pisano (2018) and Guo (2015) both focused on enhancing SPP excitation efficiency. Pisano (2018) achieved this through oblique incidence on metallic ridges, while Guo (2015) used a single deep subwavelength slit to improve SPP excitation on metals [9,10].

Surface plasmon polaritons (SPPs) are collective oscillations of electrons at the interface between a metal and a dielectric. Efficient excitation of stripe-based leaky surface plasmon polaritons (LSPPs) has attracted significant attention due to their potential applications in various fields. In this literature review, we will explore the recent research findings related to the efficient excitation of LSPPs in the Kretschmann configuration and identify potential future research directions.

Zhong et al. (2016) conducted a study on the mapping of surface plasmon dispersion in thin Ag–Au layered composite films. The authors found that the dispersion of LSPPs in thin metal films can be manipulated by controlling the composition and thickness of the film. This finding suggests that the efficient excitation of LSPPs in the Kretschmann configuration can be achieved by engineering the material properties of the metal film [11].

Zhang et al. (2020) investigated the efficient excitation of LSPPs in ultrathin InP annular nanohole arrays for light absorption solar cells. The authors demonstrated that the excitation of LSPPs in the annular nanohole arrays is attributed to the harvest of broadband and wide-angle incident light. This finding indicates that the geometry and structure of the substrate play a crucial role in the efficient excitation of LSPPs [12].

Chung et al. (2019) evaluated the electrocatalytic glycerol oxidation enabled by SPP-induced hot carriers in the Kretschmann configuration. The authors reported a significant enhancement in the photon-to-hot carrier conversion efficiency compared to neat Au film. This result highlights the potential of LSPPs in enhancing photoelectrochemical processes for energy conversion applications [13].

Aydinli et al. (2016) investigated slow plasmons in grating cavities and their implications for LSPP excitation. While no specific finding related to LSPP excitation was provided, this study suggests the importance of cavity structures and their impact on the excitation of LSPPs in the Kretschmann configuration [14].

The research findings discussed above provide valuable insights into the efficient excitation of LSPPs in the Kretschmann configuration. However, several knowledge gaps and potential future research directions can be identified based on these findings. Firstly, the impact of material composition, film thickness, and substrate geometry on LSPP excitation requires further investigation to optimize the efficiency of LSPP-based devices. Additionally, the role of cavity structures and slow plasmons in LSPP excitation needs to be explored in more detail to understand their potential contributions.

3. SIMULATION METHOD AND STRUCTURE

Simulations were conducted under the assumption of a p-polarized plane-wave serving as an incident optical beam, directed into the near end of a uniform gold layer connected to a lengthy gold stripe, as illustrated in Fig. 1. The incident beam was illuminated at a specific angle (θ) from the backside of a prism, following the Kretschmann configuration presented in Fig. 1 (a). Employing the three-dimensional finite difference time domain (3D-FDTD) method, the numerical solution of Maxwell's equations for leaky surface plasmon modes was carried out. Here, \mathbf{E} and \mathbf{H} represent the electric and magnetic field intensity vectors, respectively. Additionally, a commercially available laser beam with a wavelength of 980 nm and an intensity of $40 \mu\text{W}/\mu\text{m}^2$, as utilized in [4-6], was assumed for the simulations.

4. SIMULATION RESULTS AND DISCUSSIONS

In the initial stage, we computed the leaky mode profile for a uniform gold layer and subsequently coupled this mode to the tapered structure, as schematically depicted in Fig. 1 (b). The angle dependence ($55^\circ \leq \theta \leq 70^\circ$) of leaky surface plasmon modes along the x-axis in the presence of a uniform gold layer is illustrated in Fig. 2. The optimal coupling of photon-plasmon corresponds to higher mode intensity. Therefore, as evident from the figure, around $\theta = 64.8^\circ$, denoted as the critical coupling angle (θ_C), the mode intensity attains a significant value. At this angle, the wavevector of photons coincides with the wavevector of leaky surface plasmons, efficiently exciting them. The angle of illumination throughout the remainder of the paper is assumed to be equal to $\theta_C=64.8^\circ$.

Various tapering angles (φ) were considered with a fixed width of the stripe set to $1 \mu\text{m}$. The choice of a $1 \mu\text{m}$ width for the stripe was made to exclusively excite the fundamental leaky surface plasmon polariton mode at the specified wavelength. Opting for a larger stripe width may lead to the appearance of higher modes with multiple maxima along the width of the stripe, complicating comparisons. The simulation results, presented in Fig. 3, indicate that as the tapering angle increases from 26.7° to 78.7° , the intensity of the propagating surface plasmon mode enhances. This trend is attributed to the movement of the focal point when the focusing angle changes.

For a clearer comparison, Fig. 3 (d) displays the sampled mode intensity profile along the y-axis for different $26.7^\circ \leq \varphi \leq 78.7^\circ$. For instance, this figure reveals that the maximum mode intensity for $\varphi=45^\circ$ is approximately $|\mathbf{E}|^2=6 \times 10^{11} (\text{V/m})^2$. Additionally, the simulation results demonstrate that by tapering the near end of the stripe (Fig. 3 (c)), the mode intensity can increase by more than 60% compared to an untapered stripe (not shown here).

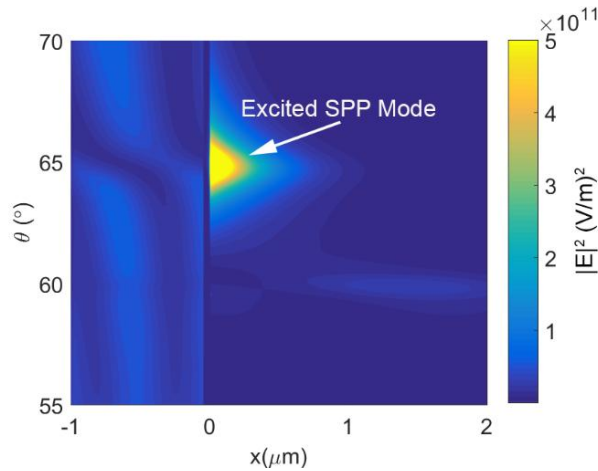


Fig. 2. Map of mode intensity profile above the uniform gold layer versus x-axis and illumination angle θ , at the near end.

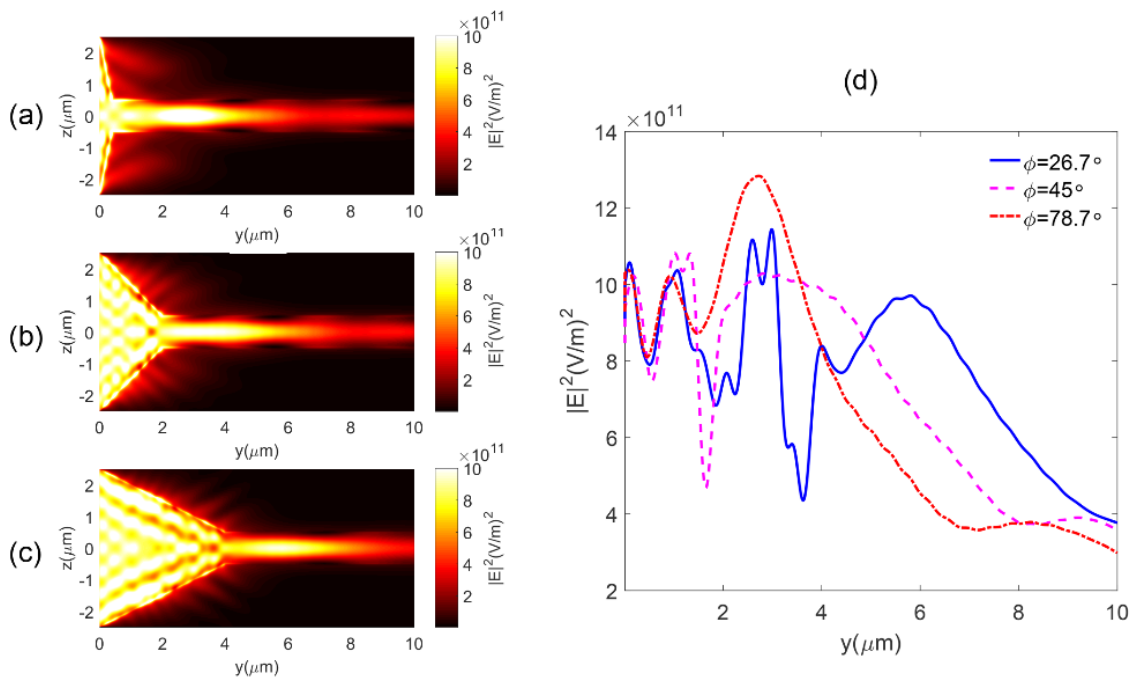


Fig. 3. Tapering angle dependencies of mode intensity profile when (a) $\phi=26.7^\circ$, (b) $\phi=45^\circ$, and (c) $\phi=78.7^\circ$, (d) mode intensity comparisons for different ϕ sampled from Fig3. (a-c) along the y-axis.

5. CONCLUSION

In a meticulous examination, the influence of the stripe tapering angle on the efficiency of surface plasmon polariton excitation using the Kretschmann configuration has been investigated. The simulation results highlight a significant enhancement in mode intensity, surpassing 60%, achievable with the precise design of the tapering angle. This suggests a potential breakthrough, as the innovative structure emerges as a strong contender for the development of integrated optical manipulation chips. These chips are strategically positioned to adeptly capture both micro- and nano-particles, signifying a noteworthy advancement in optical trapping technologies. The findings underscore the transformative potential of this design, paving the way for enhanced applications in fields such as biophysics, nanotechnology, and optical sensing.

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Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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REFERENCES

- [1] Kretschmann, E. (1971). Die Bestimmung optischer Konstanten von Metallen durch Anregung von Oberflächenplasmaschwingungen. *Zeitschrift für Physik A Hadrons and Nuclei*, 241(4), 313–324. doi:10.1007/bf01395428
- [2] Zhang, J., Zhang, L., & Xu, W. (2012). Surface plasmon polaritons: physics and applications. *Journal of Physics D: Applied Physics*, 45(11), 113001. doi:10.1088/0022-3727/45/11/113001
- [3] Zia, R., Selker, M. D., & Brongersma, M. L. (2005). Leaky and bound modes of surface plasmon waveguides. *Physical Review. B, Condensed Matter and Materials Physics*, 71(16). doi:10.1103/physrevb.71.165431
- [4] Wang, K., Schonbrun, E., Steinvurzel, P., & Crozier, K. B. (2010). Scannable plasmonic trapping using a gold stripe. *Nano Letters*, 10(9), 3506–3511. doi:10.1021/nl101653n
- [5] Ghorbanzadeh, M., Moravvej-Farshi, M. K., & Darbari, S. (2015). Designing a plasmonic optophoresis system for trapping and simultaneous sorting/counting of micro-and nano-particles. *Journal of Lightwave Technology*, 33(16), 3453–3460.
- [6] Ghorbanzadeh, Mostafa, Moravvej-Farshi, M. K., & Darbari, S. (2017). Plasmonic optophoresis for manipulating, in situ position monitoring, sensing, and 3-D trapping of micro/nanoparticles. *IEEE journal of selected topics in quantum electronics: a publication of the IEEE Lasers and Electro-optics. Society*, 23(2), 185–192. doi:10.1109/jstqe.2016.2593008
- [7] Palomba, S., & Novotny, L. (2008). Nonlinear excitation of surface plasmon polaritons by four-wave mixing. *Physical Review Letters*, 101(5), 056802.

- [8] Vinogradov, A. P., Dorofeenko, A. V., Pukhov, A. A., & Lisiansky, A. A. (2018). Exciting surface plasmon polaritons in the Kretschmann configuration by a light beam. *Physical Review. B*, 97(23). doi:10.1103/physrevb.97.235407
- [9] Pisano, E., Garcia-Ortiz, C. E., Armenta-Monzon, F., Garcia-Mendez, M., & Coello, V. (2018). Efficient and directional excitation of surface plasmon polaritons by oblique incidence on metallic ridges. *Plasmonics*, 13(6), 1935-1940.
- [10] Guo, Y., Yang, J., & Li, K. (2016). Highly efficient excitation of surface plasmon polaritons under asymmetric dielectric surroundings. *Plasmonics*, 11, 11-15.
- [11] Zhong, C., Ballantine, K. E., Kervick, C., Smith, C. M., Mullarkey, D., Shvets, I. V., ... McCloskey, D. (2016). Mapping of surface plasmon dispersion in thin Ag–Au layered composite films. *Journal of the Optical Society of America. B, Optical Physics*, 33(4), 566. doi:10.1364/josab.33.000566
- [12] Zhang, Z., Zhou, J., Wu, Y., Xia, Z., & Qin, X. (2020). Ultrathin InP annular nanohole arrays for efficient light absorption solar cells. *Applied Physics Letters*, 116(11), 113903. doi:10.1063/1.5143452
- [13] Chung, K., Zhu, X., Zhuo, X., Jang, Y. J., Choi, C. H., Lee, J. S., ... Kim, D. H. (2019). Electrocatalytic glycerol oxidation enabled by surface plasmon polariton-induced hot carriers in Kretschmann configuration. *Nanoscale*, 11(48), 23234–23240. doi:10.1039/c9nr07846k
- [14] Aydinli, A., Karademir, E., Balci, S., & Kocabas, C. (2016). Slow plasmons in grating cavities. In S. M. Shahriar & J. Scheuer (Eds.), *Slow Light, Fast Light, and Opto-Atomic Precision Metrology IX*. doi:10.1117/12.2220199