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A deep subwavelength cavity formed by total external reflection of surface plasmon polariton

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We numerically analyze the characteristics of a nanocavity in surface plasmon polariton (SPP) modes confined by total external reflection (TER) at deep subwavelength scales. This SPP-TER cavity consists of a low-index dielectric channel on a flat metal surface covered by a high-index gain medium. Compared to other types of nanocavities formed by total internal reflection such as a metallic channel and a high-index dielectric channel, an SPP-TER nanocavity provides superior functionality on mode area, confinement factor in the gain medium, Q-factor, and threshold gain. From this result, we suggest the SPP-TER nanocavity as a promising high-quality deep-subwavelength scale resonator, which is an essential ingredient in nanophotonics.

I. INTRODUCTION

Many dielectric-loaded surface plasmon polariton (SPP) schemes have been developed using a dielectric channel directly on a metallic surface, such as directional couplers, splitters, and resonators. Introducing a high-index dielectric ridge could enhance fields confined by total internal reflection (TIR) in SPP modes, but device performance was often hampered by increased transmission loss caused by the high effective index of SPP-TIR modes. One way of reducing the loss in SPP-TIR devices is embedding gain materials in the high-index region to compensate for the propagation loss. In another approach, a low-index buffer channel can be used between the metal and the high-index region, and then the associated hybrid plasmonic mode enables a low-loss transmission with subwavelength field confinement. For example, the high-index dielectric ridges used in SPP-TIR waveguides might have an air nanohole at the interface of the metal and the ridge. A shallow and wide air nanohole at the metal surface could result in a strong enough local field enhancement to achieve subwavelength mode confinement with relatively low transmission loss. At this point, it is worth noting that the SPP mode guided in the holey ridge is a TIR mode with a higher effective index than the boundary dielectrics in spite of its propagation through an air hole, and the holey ridge mode has no cutoff frequencies in the dispersion relation. A different type of SPP nanocavity exploits the phenomenon of total external reflection (TER), which is one of the unique features of SPP. The SPP-TER mechanism, which confines more energy in the low-index region than in the adjacent high-index region, is based on the relative dispersive characteristics of different SPP modes supported by certain cutoff conditions within a finite but wide frequency regime. When an SPP mode propagating on a metal surface meets the boundary of the metal surface covered by a different dielectric with a higher index, SPP-TER mode can no longer propagate forward and must be reflected back completely. Therefore, an SPP-TER mode excited on a finite-length “low-index core” covered by a “high-index cladding” on a metal surface can be confined with extremely high reflectance at both the lateral and longitudinal boundaries. In this paper, we numerically analyze the characteristics of an SPP-TER nanocavity, which consists of a low-index channel on a metal surface covered by a high-index gain medium. The channel design has a longitudinal cavity at the wavelength scale and a lateral thickness of only a few nm. Even when we reduced the low-index channel thickness to ~1 nm, we were able to confine an SPP-TER mode under $\lambda/2$ scale and guide it into the longitudinal direction with almost 100% reflection at both ends. This is a big contrast to the TIR-based dielectric resonators, whose modal volume diverges as the lateral cross-section becomes smaller than $\lambda^2$. Other two parameters of the resonators, confinement factor and cavity Q-factor, are compared with those of SPP-TIR schemes which have high-index dielectric or metallic channels for the cavity. By virtue of the TER mechanism, the SPP-TER cavity provides a higher Q-factor than SPP-TIR cavities, especially ~5 times higher than dielectric-SPP-TIR cavities for a certain frequency range. The threshold gain of SPP-TER is always lower, at least several times for fundamental mode, than in SPP-TIR cases over wide ranges of the frequency and system dimensions. Therefore, SPP-TER nanocavities with a guiding channel only a few nm thick embedded in a gain medium can be a good candidate for a high-Q nano-resonator with small operational energy.

II. SYSTEM DESIGN OF AN SPP-TER CAVITY AND ITS DISPERSION RELATION

The SPP-TER nanocavity studied in this work is schematically depicted in Fig. 1. A low-index ($\varepsilon_{\text{low}}$) dielectric channel (length: $l$, thickness: $t$, and width: $w$) is covered by high-index ($\varepsilon_{\text{high}}$) dielectric cladding on a metal ($\varepsilon_{\text{m}}$) substrate. In the design and analysis, we set the channel length $l$...
to be longer than \( t \) and \( w \), and the thickness of the high-index cladding is infinite. It is interesting to see that the “low-index” channel in the SPP-TER nanocavity acts like the “high-index” core of optical fibers in the sense of that certain SPP modes at a finite frequency range can be excited and confined only in the low-index region. This contradictory behavior can be attributed to a unique behavior of TER allowed in SPP modes. The cut-off frequencies of two SPP modes at the \( \varepsilon_m/\varepsilon_{low} \) \( (\varepsilon_m/\varepsilon_{high}) \) interfaces are given as \( \omega_{low(high)} = \omega_p/\sqrt{1 + \varepsilon_{low(high)}} \), where \( \omega_p \) is the plasma frequency of metal. Therefore, an SPP mode in the frequency range of \( \omega_{high} < \omega < \omega_{low} \) can propagate only through the \( \varepsilon_{low} \) channel and must be bounded by total reflection from the external \( \varepsilon_{high} \) boundaries for all propagation directions.

These cutoff behaviors of SPPs are described in detail by the dispersion curves shown in Figs. 2(a) and 2(b). The fundamental SPP-TER modes are calculated by a effective index method.\(^\text{14,16}^\) The permittivity of silver \( \varepsilon_{Ag} \) is chosen by the Drude model using the experimental data:\(^\text{17}^\) \( \varepsilon_{Ag}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \), where \( \varepsilon_{\infty} = 3.7 \), \( \gamma = 3.226 \times 10^{13} \) s\(^{-1}\), and \( \omega_p = 1.391 \times 10^{16} \) s\(^{-1}\). The permittivity of the dielectric media is assumed to be \( \varepsilon_{low} = 2.1 \) and \( \varepsilon_{high} = 8.4 \). The horizontal dashed lines at \( \omega_{low(high)} \) = 0.415(0.287) \( \times \) \( \omega_p \) are the cut-off frequencies of SPP modes excited on the flat metal-dielectric interfaces. \( \beta \) is the propagation constant of the SPP mode and \( k_p = \omega_p/c \). The dotted gray curves denoted by A and B, respectively, represent the dispersion relations of SPP modes at the \( \varepsilon_{Ag}/\varepsilon_{low} \) and \( \varepsilon_{Ag}/\varepsilon_{high} \) interfaces, and the dispersion curve C (dotted blue) is for the \( \varepsilon_{Ag}/\varepsilon_{low}/\varepsilon_{high} \) three-layered slab structure for \( t = 2 \) nm.\(^\text{18}^\) The two dashed-dotted gray lines are the light lines for \( \varepsilon_{low} \) and \( \varepsilon_{high} \) media. The dispersion relations (solid curves in Figs. 2(a) and 2(b)) allow SPP modes in the low-index channel within the frequency range of \( \omega_{high} < \omega < \omega_{low} \) and in the \( \varepsilon_{high} \) light-line. As \( t \) increases for a fixed \( w \) (= 50 nm in Fig. 2(a)), the curves move toward A (dispersion at the \( \varepsilon_{Ag}/\varepsilon_{low} \) interface), and the propagation length \( L = 1/2\Im(\beta) \) becomes longer for a fixed operation frequency \( \omega \). The same trend can be seen for a decreasing \( w \) with a fixed value of \( t (= 2 \) nm in Fig. 2(b)). Here, two selected operation frequencies at \( \omega_{1,2}/\omega_p = 0.356, 0.294 \) are shown in green horizontal lines. Note that there is no allowed SPP mode at \( \omega_2 \) for \( t = 8 \) nm, as can be seen in (a), demonstrating that only a few nm range of the \( \varepsilon_{low} \) channel thickness supports the SPP-TER mode.

### III. CHARACTERISTICS OF SPP-TER CAVITIES

To elucidate the superior performance of the SPP-TER system, we compare it with two hybrid SPP nanocavities operating in TIR modes: a \( \varepsilon_{high} \)-dielectric nanorod (D-NR)\(^\text{11}^\) and a \( \varepsilon_{Ag} \)-metallic NR (M-NR), as depicted in Fig. 3. By the calculation based on a finite-element method (FEMLab COMSOL), the field amplitude \( (H_z) \) distribution for each structure in the \( xy \) cross-sectional plane is obtained as shown in the middle row for system parameters of \( t = 5 \) nm and \( w = 50 \) nm. All three structures show well confined field distributions in the low-index (\( \varepsilon_{low} \)), narrow gap region. The field amplitude maxima appear on the Ag surface, as shown in the cross-section profiles (red curves in the bottom). This shows that the evanescent characteristic of SPP waves formed in all three systems.

![FIG. 2](image-url)
In Fig. 4, three key resonator parameters—(a) mode areas, (b) propagation loss, and (c) confinement factors—are compared among the three types of nano-cavities shown above, varying the channel dimensions of $w$ and $t$. Here, the mode area is normalized by $(\lambda_0/2)^2$, where $\lambda_0$ is the wavelength in vacuum. The mode area monotonously decreases with decreasing $w$ for SPP-TER and M-NR. In contrast, for small values of $w (<50 \text{ nm})$, the mode area of D-NR increases again as the channel size decreases because the cross-section area of D-NR becomes too small to allow the photonic modes due to the asymmetric dielectric waveguide nature. Therefore, D-NR has a limitation in miniaturizing the system.

There is a trade-off between the mode area and the propagation loss because a larger mode area provides fewer fields in metal. Therefore, the propagation loss in M-NR and SPP-TER is larger than in D-NR for a small channel size as can be seen in Fig. 4(b). The propagation loss can be compensated if we replace $\varepsilon_{\text{high}}$ with gain medium. To have a larger modal gain, more of the fields need to be in the $\varepsilon_{\text{high}}$-gain medium. To quantify this, we introduce the confinement factor $\Gamma$, which is the electric field energy in the $\varepsilon_{\text{high}}$-gain medium divided by the total electric energy. As shown in Fig. 4(c), when the channel width $w$ is suitably large (>400 nm), the three structures have almost same $\Gamma$; however, they show much different behavior as the channel gets narrower. In M-NR, $\Gamma$ reduces dramatically as the channel width shrinks because the mode profile (distribution) moves from $\varepsilon_{\text{high}}$ to the metal channel area. Consequently, M-NR

**FIG. 3.** Cross-sectional diagrams of (a) SPP-TER, (b) D-NR, and (c) M-NR nanocavities (first row) and their field ($H_x$) distributions in the $xy$- (middle row) and $yz$-planes (bottom row). $\varepsilon_{\text{low}}/\varepsilon_{\text{high}} = 0.356$, $t = 5 \text{ nm}$, and $w = 50 \text{ nm}$. The bottom row shows the normalized field amplitudes along the $y$-axis at the middle position of the channel (green dashed lines in the middle row).

**FIG. 4.** Comparisons of the normalized mode area (a), the propagation loss (b), and the confinement factor (c) and (d) among SPP-TER, D-NR, and M-NR. Here, $\omega_2/\omega_p = 0.356$ in (a)-(c), and $t = 2 \text{ nm}$ and $w = 50 \text{ nm}$ in (d).
shows the smallest $\Gamma$ among the three systems. In D-NR, $\Gamma$ gradually increases with smaller width to a certain point; however, below that specific width, the mode area starts to diverge abruptly, damaging $\Gamma$. In SPP-TER, $\Gamma$ increases consistently and sharply with decreasing channel width. Here, we can see an interesting feature: the mode areas of SPP-TER and M-NR are similar to each other; however, SPP-TER can have a much larger $\Gamma$ than M-NR, and consequently the propagation loss can be much smaller than in M-NR. Therefore, we can conclude that the SPP-TER structure is superior to D-NR for a smaller mode area and to M-NR for higher confinement factor to have a lower propagation loss with implementing gain medium. Importantly, those benefits hold for the whole range of channel dimensions, justifying the possibility of realizing a deep-subwavelength resonator. Figure 4(d) shows the dependency of $\Gamma$ on the operation frequency ($\omega_{\text{high}}^c < \omega < \omega_{\text{low}}^c$). Here, the channel dimension is fixed as ($t$, $w$) = (2 nm, 50 nm). In SPP-TER, $\Gamma$ monotonously increases as $\omega$ decreases. As discussed in Fig. 2, higher frequency allows a mode with a larger propagation constant, and the field localization is getting stronger in $\omega_{\text{low}}$. Therefore, the field distribution in $\omega_{\text{high}}^c$ reduces with decreasing $\Gamma$. The tendency of $\Gamma$ at a high frequency ($\omega > 0.38\omega_p$) is alike in all structures. However, in the range of $\omega_{\text{high}}^c < \omega < 0.33\omega_p$, the difference in confinement factor becomes noticeable, and SPP-TER has a larger $\Gamma$ than the other two systems in all of the allowed frequency range.

From the cutoff mechanism of SPP-TER in the frequency region of $\omega_{\text{high}}^c < \omega < \omega_{\text{low}}$, no SPP mode can exist in the $\varepsilon_{\text{high}}/\varepsilon_{\text{Air}}$ interface. Thus, the SPP-TER modes reveal almost unit reflectance at the end face of resonator over the cutoff frequency range as shown in Fig. 5(a). A standing wave ratio method is applied in obtaining the reflectance $R = R(\omega)$. The $Q$-factor of the SPP-TER resonator can be defined by

$$Q = \frac{2n\omega}{c} \left( \frac{1}{3\lambda - 2\ln R} \right),$$

where $n$ is the effective index of SPP-TER modes, $\lambda$ is the cavity length, and $\alpha$ is the attenuation coefficient given by propagation loss. The $Q$-factor in Eq. (1) is depicted as a function of $\omega$ in Fig. 5(b). The SPP-TER mode has a higher $Q$-factor than the others in a wide frequency range above 0.32 $\omega_p$ and reveals a $Q$-factor comparable to M-NR as the frequency approaches the cutoff limits of $\omega_{\text{high}}^c$ and $\omega_{\text{low}}^c$.

A higher $Q$-factor and larger confinement factor are favorable to increase the modal gain and consequently to have a smaller threshold gain. To examine the practical possibility as a resonator, we considered ZnSe as the $\varepsilon_{\text{high}}$ medium. The emission transition frequency (vertical black dashed-lines in Fig. 5) of ZnSe, $\omega_{\text{ZnSe}} = 0.294 \times \omega_p$, is placed near $\omega_{\text{high}}^c$ where a high confinement factor is expected as can be seen in Fig. 4(d). The threshold condition for a lossy cavity is generally given as follows:

$$\Gamma g_{\text{th}} = \frac{1}{L} + \frac{1}{l} \ln \frac{1}{R},$$

where $L = 1/2\text{Im}[\beta]$ is the propagation length. The threshold gain $g_{\text{th}}$ is shown in Fig. 6, together with the gain coefficient of ZnSe (horizontal black dashed-line) determined by $g_{\text{ZnSe}} = -\omega \text{Im}[\varepsilon_{\text{gain}}]/(c \varepsilon_{\text{gain}}) = 5.03 \times 10^5 \text{cm}^{-1}$. $\varepsilon_{\text{gain}}$ is calculated using the Lorentz oscillator model: $\varepsilon_{\text{gain}}(\omega) = \varepsilon_{\infty} + \frac{\omega_0^2}{(\omega_0^2 - \omega^2 + i\gamma_\omega)}$, $\varepsilon_{\infty} = 8.38$, $\gamma_\omega = 3.84 \times 10^{10} \text{Hz}$, and $f = 10^{-4}$. The threshold gain of SPP-TER is always smaller for all cavity-mode orders than those of two TIR cavities. Especially for the fundamental cavity modes.
(m = 1), only the SPP-TER threshold is below the \( g_{ZnSe} \), and at least several times smaller than in TIR cases. In spite of the small propagation loss of the D-NR shown in Fig. 4(b), its threshold gain is larger because the D-NR confinement factor and reflectance at \( \omega_2 \), respectively, in Figs. 4(d) and 5(a) are much smaller than those of the SPP-TER. For \( w > 80 \text{ nm} \), the threshold gain of M-NR is placed between the other cases.

**IV. CONCLUSION**

Based on the unique property of SPP modes, total external reflection characteristics of the deep subwavelength SPP-TER nanocavities are theoretically evaluated. Two other nanocavities based on the total internal reflection of SPP, D-NR, and M-NR, are compared in terms of mode area, propagation loss, confinement factor in the gain medium, Q-factor, and threshold gain. For D-NR, the propagation loss is smaller than for the other structures, but the mode area diverges at small system dimensions, resulting in the smallest Q-factor among the three structures due to its low reflectance at the boundaries. M-NR has a small mode area but low confinement factor and large propagation loss; therefore, it reveals a large threshold gain for the fundamental mode. For SPP-TER, on a comparison, the cutoff-frequency properties of the SPP modes excited on a lower-index core allow almost unit reflectance and consequently higher Q-factor over a wide frequency. Therefore, this TER mechanism of SPP modes would contribute to reduce the required pump current density for loss-compensation via gain in realizing deep-subwavelength resonators for nanophotonic applications, even though implementing the system seems to be challenging.27

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