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Field enhancement by longitudinal compression of plasmonic slow light

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We propose a new approach for field enhancement by using plasmonic slow light (PSL), which is one of the phenomena unique to surface plasmon polariton (SPP). PSL shows a remarkably low group velocity and high field confinements beyond the diffraction limit. This phenomenon induces “longitudinal compression” of optical energy in nanoscale regions, resulting in a large field enhancement. The longitudinal compression by PSL opens a new dimension for field enhancement by SPP propagation. This approach will be applied to various prospective applications based on field enhancement in nanoplasmonics. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3691227]

I. INTRODUCTION

Nanoplasmonics—the science and technology based on surface plasmon polariton (SPP) in nanoscale regions—has attracted significant interest recently. SPP offers large wave vectors and high field confinements on a metal surface beyond the diffraction limit, which opens unique prospects for the design of nanophotonic devices. The recent rapid progress in nanoplasmonics has been based on the enhancement of electromagnetic fields and its applications. The large fields nanolocalized by highly confined SPP offer benefits in nonlinear optical effects, detectors, sensors, and nanoimaging.1–3

One of the effective approaches for field enhancement is slow light, which is light with a remarkably low group velocity, inducing field enhancement by spatial compression of optical energy. Recently, the existence of slow SPP waves, which we call plasmonic slow light (PSL), has been reported as a phenomenon unique to SPP. PSL will show characteristics of both SPP and slow light, such as large wave vectors, high field confinements, and spatial energy compression, which leads to giant nanolocalized fields. PSL has the possibility for being a new approach for field enhancement. However, although PSL itself, as a value of the group velocity, has been studied before, the analysis for the application of PSL effects, especially field enhancement, has not been reported.

In this paper, we report the theoretical analysis of field enhancement by longitudinal compression of PSL. We observed field enhancement as one of the PSL effects by using the abrupt mode conversion between PSL and long-range SPP (LR-SPP), known as long propagation SPP and “fast light”, in the finite-difference time-domain (FDTD) simulation. When a LR-SPP pulse reaches the PSL region, the front of the pulse, entering the PSL region first, will propagate remarkably slowly and then the back of the pulse will catch up. As a result, the pulse will be confined in less space along the propagation direction and its field intensity will thereby be enhanced, even if metal losses exist. The spatial compression along the propagation direction is a new dimension for field enhancement by SPP propagation. The concept of longitudinal compression by PSL will allow us to develop various applications based on field enhancement in nanoplasmonics.

II. COUPLING STRUCTURE DESIGN AND MODE ANALYSIS

For a mode conversion, an adiabatic coupling is usually efficient. However, as for SPP, if it gradually changes into a PSL that has a high propagation loss, the intensity will decay along the mode conversion and it will be not efficient for field enhancement. Therefore, we propose the abrupt mode conversion by the coupling between PSL and LR-SPP for the efficiency. Figure 1 shows the coupling structure between PSL and LR-SPP, which we call a hetero-insulator-metal-insulator (IMI) waveguide; it consists of a SiO2–Ag–SiO2 (a LR-SPP region) and a Si–Ag–Si (a PSL region) plasmonic waveguide. In IMI waveguides, the SPPs on two interfaces propagate as a complementary coupled mode and show either the characteristic of LR-SPP or PSL, depending on the structure.21–27 Figure 2(a) shows the dispersion relations of the SiO2–Ag–SiO2 and the Si–Ag–Si plasmonic waveguide with the film thickness h = 28 nm. We calculated the dispersion relations, including the loss factor, using the relative permittivity of a metal and a dielectric, defined by the Drude model and the Sellmeier equation, respectively.

The dashed-dotted line (SiO2–Ag–SiO2) is close to the light line. It shows the LR-SPP, which has a long propagation length, even in a lossy metal.28–30 The dashed line (Si–Ag–Si) slopes sharply in comparison with the light line. It represents the PSL from the definition of the group velocity \( v_g = (\partial \beta / \partial \omega)^{-1} \), where \( \omega \) and \( \beta \) are the angular frequency and the wavenumber, respectively. These two modes show completely different characteristics with

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respect to group velocity, field confinements, and propagation length. However, the spatial field distributions show the same tendency (Fig. 1 inset), which leads to the smooth mode conversion. LR-SPP is a better candidate for the coupling with PSL than any other propagation mode. The coupling between PSL and LR-SPP is a reasonable method for the observation of the longitudinal compression by PSL.

Figure 2(b) shows the slow light properties in the Si-Ag-Si plasmonic waveguide with $h = 28$ nm. The group index $n_g = c/v_g$ is regarded as a slow-down factor from the velocity in vacuum, $c$, and the group velocity dispersion (GVD) parameter $\beta_2$ is given by $\beta_2 = d^2 \beta/d\omega^2$, which is used for assessing pulse distortion. This waveguide has $n_g = 119$ at a wavelength of 613 nm, corresponding to the point GVD = 0, where no pulse distortion occurs. The value of $n_g$ is higher than that obtained in an ordinary slow light device and sufficient for inducing longitudinal compression. The propagation length $[2 \mathrm{Im}(\beta)]^{-1}$ of this PSL is only 36 nm. This short propagation limits the range of applications, because PSL cannot reach an intended point from the excitation spot. Therefore, the connection with a long propagation mode, such as LR-SPP, is essential for utilizing PSL effects.

### III. SIMULATION RESULTS

Figure 3 shows the mode coupling in the hetero-IMI waveguide with an infinite film width and $h = 28$ nm in the FDTD simulation. The LR-SPP with a pulse width of 100 fs at a center wavelength of 613 nm is excited by a grating coupler at $x = -2.4 \mu m$ and propagates in the hetero-IMI waveguide. At the interface between SiO$_2$ and Si, some reflection of LR-SPP occurs (the 22% reflection is observed), owing to the no-adiabatic coupling. However, most SPP waves enter the PSL region and are compressed dramatically around the metal film. Their wavelength shows good agreement with that of PSL; thus, we can say that the compressed SPP is the PSL excited by LR-SPP. This smooth mode conversion occurs because of the similar field distributions of PSL and LR-SPP.

To obtain the $n_g$ of the PSL, we observed the temporal pulse shapes at each propagation distance from the interface, as shown in Fig. 4. At the 20 nm propagation distance, the peak intensity reaches the maximum and SPP waves propagate for dozens of nanometers in the PSL region (a propagation length of 45 nm is obtained). Hence, it is estimated that LR-SPP is converted into PSL completely at this point. The time shift from this point to the 60 nm propagation distance is 13.4 fs. This value represents $n_g = 100$, which is in good agreement with the numerical analysis. Note that this coupling realizes the abrupt large slow-down of SPP propagation.
only by the variation of dielectrics. Moreover, PSL can be induced in various dielectrics that have a relatively high refractive index. In contrast, periodic structures that exploit Bragg scattering, such as a photonic crystal that is an ordinary slow light device, need a complicated nanostructure to induce slow light and the variety of dielectrics is limited. In Fig. 5, we display the amplitude of the electronic field intensity $|E_z|^2$ in the hetero-IMI waveguide. In the LR-SPP region, the electric field extends mostly in SiO$_2$ and its wavelength is similar to that of light in SiO$_2$. On the other hand, the SPP pulse in the PSL region is dramatically compressed relative to that in the LR-SPP region, and simultaneously, their amplitude is strongly enhanced. At a point 20 nm away from the interface, on the metal surface in the PSL region, about 10-fold enhancement of electrical field intensity is obtained, as compared to the intensity of the input LR-SPP. We are sure that this field enhancement is caused by the longitudinal compression of PSL. In addition, the electric field shows high confinements near the metal surface in the PSL region. If these fields were used to induce nonlinear optical effects, such as third-harmonic-generation in silicon, they would be enhanced by 2-3 orders of magnitude by highly confined PSL beyond the diffraction limit. The further enhancement of nonlinear optical effects by many orders of magnitude can be achieved by “transverse compression”, i.e., superfocusing in tapered plasmonic waveguides. Note that the longitudinal compression by PSL can be combined with the transverse compression, because the longitudinal compression is induced by the variation of dielectrics, not a structure shape. Therefore, two or three dimension compression of the SPP can be achieved, leading to further field enhancement. In addition, the coupling geometry was not optimized for the efficiency of the mode conversion in this study; hence, modification, such as impedance matching, can lead to further enhancement of optical intensity.

IV. CONCLUSION

We reported a new approach for field enhancement by PSL. We showed, theoretically, that field enhancement is one of the effects of the longitudinal compression of the PSL, and proposed the coupling structure between PSL and LR-SPP, which is a simple and efficient way for field enhancement by PSL. The PSL has two specific characteristics: a high group index and high field confinements. These factors induce large field enhancement and lead to the strong interaction between electromagnetic fields and materials in nanoscale regions. This phenomenon can be applied to nonlinear optical applications, such as a nanoconfined light source based on high harmonic generation. Although we focused on PSL in IMI plasmonic waveguides in this study, PSL can exist in other plasmonic waveguides, i.e., metal-insulator-metal plasmonic waveguides, dielectric-loaded plasmonic waveguides, nanowires, and nanotubes. The phenomenon analyzed here can be applied to these waveguides, and they will be a powerful platform for large field enhancement in nanoscale regions. We expect that our findings will open the way to the development of various optical devices with slow light and will further highlight the wide photonic functionality made available by nanoplasmonics.

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