Giant modal gain, amplified surface plasmon-polariton propagation, and slowing down of energy velocity in a metal-semiconductor-metal structure

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(Received 28 August 2009; published 12 October 2009)

We investigate surface plasmon-polariton (SPP) propagation in a metal-semiconductor-metal structure where semiconductor is highly excited to have an optical gain. We show that near *the SPP resonance*, the imaginary part of the propagation wave vector changes from positive to hugely negative, corresponding to an amplified SPP propagation. The SPP mode experiences an unexpected *giant modal gain* that is 1000 times of material gain in the excited semiconductor, a phenomenon not known to exist in any other system. We show that the physical origin of such giant gain is the slowing down of average energy propagation in the structure.

DOI: 10.1103/PhysRevB.80.153304 PACS number(s): 73.20.Mf, 71.45.Gm, 73.21.Ac, 78.20.Bh

Interactions between photons and quasiparticles (or collective excitations) such as plasmons and excitons are not only of great importance in many areas of fundamental physics but also underpins many modern technologies. Recent study of similar interactions has led to physics understandings and discovery of phenomena in connection with various quasiparticles or collective excitations.[1] The current interest in these collective excitations such as surface plasmon-polaritons (SPPs) centers mostly at nanoscale,[2–9] where many interesting issues such as active plasmon excitations, extremely intense field, and large field gradient near metal surfaces re-emerged with greater importance than ever before. Technologically, understanding of such interactions at nanoscale could lead to many device applications such as truly nanoscale lasers, detectors, solar cells with unprecedented performance and functionalities. SPPs and surface plasmon amplification by stimulated emission of radiation (SPASERs) (Ref. 3) are best examples that show how to take advantages of understanding of nanoscale physics to make a potentially arbitrarily small nanophotonic device.

Semiconductor nanostructures integrated with metallic structures are known to be able to guide or confine optical waves in a much smaller space dimension than the wavelength involved or the diffraction limit, thus becoming a natural choice for making nanophotonic devices such as nanowaveguides and nanolasers. The detrimental loss in metals has been the main roadblock, leading to diminishing propagation length in a waveguide or insurmountable threshold gain for a nanolaser. Thus it is quite natural to consider integrating metals with semiconductor gain medium to compensate the metal loss[5] and to even provide net gain for an active device. Among various structures that support SPP modes, metal-semiconductor-metal (MSM) structure is the canonical example and has attracted a great deal of attention recently for applications in active nanophotonic devices.[7,8] Compensation of metal loss for a propagating mode in a MSM structure was studied[4] at wavelength around 1.5 microns, which is far below plasmon resonance. It was shown[5] that a large net modal gain is possible in a semiconductor-metal core-shell structure. The experimental demonstration of lasing in similar structure[7] partially verified the existence of this net gain. While possibility of any net gain in a MSM structure is important, the frequency range of positive modal gain is near the cutoff frequency which is well-below SPP resonance.[6] Since the effective wavelength near the cutoff is very long, a key promise of plasmonic devices, the wavelength reduction or compression, is not possible far below resonance. Since the effective wavelength is the shortest near the SPP resonance, it is highly desirable to achieve a net gain near the SPP resonance. In that scenario, one would be able to achieve maximum reduction in wavelength (and device size) and positive gain simultaneously, making the smallest active devices possible. However, so far no theory or experiment has shown net optical gain in a MSM waveguide that can significantly overcompensate the metal loss near the SPP resonance. Here we demonstrate that, not only a net modal gain exists in the MSM structure near the SPP resonance, but the gain is hugely enhanced. In particular, we discovered the existence of a *giant modal gain* that can be as large as 1000 times the semiconductor material gain. Such a giant gain is not known to exist in any other situations. Furthermore, we show that the physical origin of this giant gain is the significant slowing down of the average energy velocity near the SPP resonance in the structure.

We investigated the MSM plasmonic waveguide as a model system with special attention paid to the possibility of an overall optical gain for the guided modes *near the SPP resonance*. The loss compensation has been studied for similar structure for infrared wavelength, that is, far below the SPP resonance.[4] The MSM waveguide consists of a thin semiconductor layer of thickness d sandwiched between two thick enough (usually larger than 100 nm) metal layers. We assume that the modes are confined transverse to the layers (x direction) and uniform in y direction and propagating along z direction. The semiconductor has a dielectric constant ε_1 with a real part of 12 and the metal is silver with dielectric function $\varepsilon_2(\omega)$ taken from Ref. 10 and curve fitted for our numerical solution. All energy-loss channels from semiconductor to metal are contained in the experimentally determined dielectric function $\varepsilon_2(\omega)$ for silver. The material gain in the semiconductor can be modeled by adding a small negative imaginary part ε_1'' to the dielectric constant and the material gain is given by $G_0=-\varepsilon_1''\omega/(nc)$, where n is the real part of refractive index. As we will show in the later part of

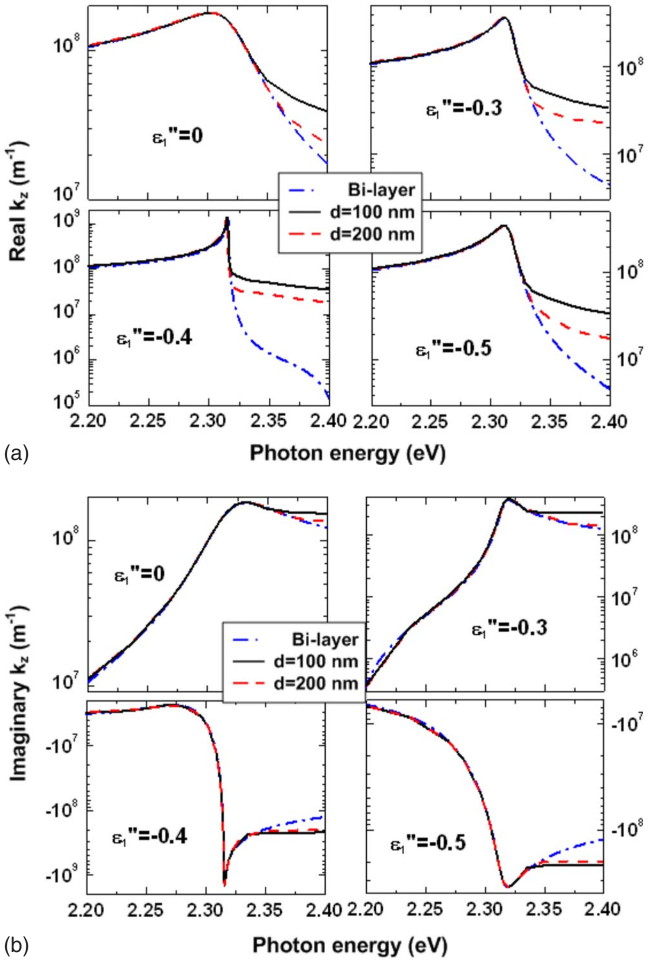

FIG. 1. (Color online) (a) Real and (b) imaginary parts of wave vector k_z versus photon energy for $d=100$ nm (solid) and 200 nm (dash) for the MSM structure or for the bilayer MS structure (dash dot).

this Brief Report, such a frequency independent ε_1'' can be justified by using a more realistic gain model. For the symmetric TM modes, the dispersion relation is determined by

$$\varepsilon_2 k_1 \tanh(k_1 d/2) = -\varepsilon_1 k_2, \tag{1}$$

and the propagation wave vector is defined by

$$k_z^2 = \varepsilon_{1,2} k_0^2 + k_{1,2}^2. \tag{2}$$

It is easy to show that the eigenvalue, Eq. (1), for the MSM structure becomes the well-known expression for the SPP mode along a MS interface in the limit of large Re$[k_1 d]$, $[\tanh(k_1 d/2) \approx 1]$: $\varepsilon_2 k_1 \approx -\varepsilon_1 k_2$. For a finite d, eigenvalue, Eq. (1), has to be solved numerically.

Figures 1(a) and 1(b) show, respectively, the real and imaginary parts of k_z (Ref. 11) as a function of photon energy with $d=100$ and 200 nm for four different values of ε_1'', compared with the dispersion relations in a MS bilayer structure. It is seen that all structures have the same behavior around SPP resonance (within a range of ± 25 meV around the peak), independent of the number of interfaces or the thickness of the middle layer. This means the guided modes in the MSM waveguide are decoupled into two independent SPP modes at the two MS interfaces. We observe in Fig. 1(a) that material gain in semiconductor layer can significantly modify the resonance behavior,[8] as can be easily seen by comparing different panels of Fig. 1(a). There exists an optimum level of semiconductor gain (around $\varepsilon_1''=-0.4$), where SPP resonance has the strongest response (with highest and narrowest resonance peak). For application of active optical devices, it is more important to study the imaginary part of k_z as it describes the optical loss or gain. The *modal gain* is given by, G_m $(=-2\ \mathrm{Im}[k_z])$, which describes the overall gain that a given mode experiences in a waveguide containing active region. For example, the intensity of a field mode traveling along the z axis of the waveguide can be written as $I=I_0 e^{G_m z}$, where I_0 is the initial intensity. The *material gain*, G_0 defined earlier, is a pure material property of the semiconductor and describes how a plane wave is amplified in an infinitely large medium without a waveguide. In a typical dielectric waveguide with gain medium, the modal gain is typically much smaller than material gain. Note that the modal gain in a MSM structure already takes into account the metal loss and is therefore a net gain for a mode. In Fig. 1(b) we see that, for small material gain (e.g., when $\varepsilon_1'' > -0.3$), Im$[k_z]$ is positive or modal gain is negative near SPP resonance due to metal loss. However, Im$[k_z]$ becomes extremely negative or modal gain becomes a giant positive value near the SPP resonance when the semiconductor material gain G_0 is large enough (or ε_1'' is enough negative). For $\varepsilon_1''=-0.4$, which corresponds to a material gain of about 1.35×10^4 cm^{-1}, the modal gain at the SPP resonance is around 2×10^7 cm^{-1} [see Fig. 1(b)], more than 1000 times larger than the material gain. Such a large modal gain has not been seen in any other systems or situations. It may sound counterintuitive that a guided mode can experience more gain (modal gain) per unit propagation length than the gain provided by the gain medium (material gain). The ratio of the two is known as *confinement factor* in conventional waveguide with a gain material and much smaller than 1 typically. For instance, a GaAs/AlGaAs waveguide with a single-quantum well has a confinement factor of 0.02–0.03. The concept of the confinement factor was indeed an issue of debate when a larger-than-unity confinement factor was first shown in the case of a semiconductor nanowire.[12] In that case, the physical origin for the larger modal gain is the group velocity [defined as $v_g=\partial\omega/\partial(\mathrm{Re}[k_z])$] slowing down dramatically in a strongly guided situation, leading to a larger optical gain per unit length than the material gain.

To understand the physical origin of the giant modal gain and to see if the huge enhancement of modal gain is related to the slowing down of group velocity, we plot in Fig. 2(a) the group velocity for $\varepsilon_1''=-0.4,-0.5$, compared with the corresponding modal gain in Fig. 2(b). As we expect, the group velocity in a plasmonic waveguide can take both positive and negative values around the SPP resonance. However, the maximum of modal gain does not correspond to any special features of the group velocity. We recall that, in a dispersive medium with loss or gain, a physically more fundamental velocity is not group velocity, but energy velocity v_E, or the velocity of energy propagation for a particular mode. Energy velocity[13] is defined as the ratio of energy flux density S over

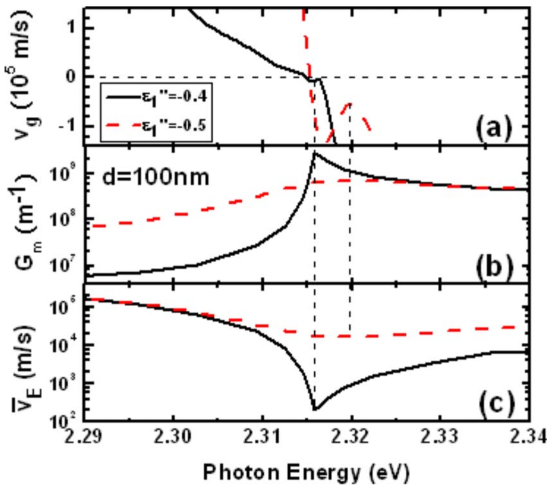

FIG. 2. (Color online) (a) Group velocity, (b) modal gain, and (c) average energy velocity versus photon energy for $\varepsilon_1''=-0.4$ (solid), -0.5 (dash) with $d=100$ nm.

stored energy density w, i.e., $v_E=S/w$. Since energy propagates in opposite directions in semiconductors and metals, an average energy velocity $\bar{v}_E$ is introduced and is given by

$$\bar{v}_E=\frac{\int w^s v_E^s d\mathbf{v}+\int w^m v_E^m d\mathbf{v}}{\int w^s d\mathbf{v}+\int w^m d\mathbf{v}}=\frac{\int S^s d\mathbf{v}+\int S^m d\mathbf{v}}{\int w^s d\mathbf{v}+\int w^m d\mathbf{v}}, \quad (3)$$

where superscripts "s" and "m" represent quantities in semiconductor and metal, respectively. The z component of the energy flux density S_z in this case can be written as

$$S_z=\frac{1}{2}\mathrm{Re}[E_x H_y^*], \quad (4)$$

and the energy density in semiconductor is defined in the usual way as

$$w^s=\frac{1}{2}\mathrm{Re}[\mathbf{E}^s\cdot\mathbf{D}^{s*}+\mathbf{B}^s\cdot\mathbf{H}^{s*}], \quad (5)$$

while energy density in metal is derived from Poynting's theorem in linear, lossy, and dispersive media[13]

$$w^m=\frac{1}{2}\mathrm{Re}\left[\frac{d(\omega\varepsilon_2)}{d\omega}\mathbf{E}^m\cdot\mathbf{E}^{m*}+\mathbf{B}^m\cdot\mathbf{H}^{m*}\right]. \quad (6)$$

Figure 2(c) shows the z component of the average energy velocity as a function of photon energy for $\varepsilon_1''=-0.4,-0.5$. It is seen that $\bar{v}_E$ has its minimum value whenever G_m is the largest. This relationship is true for all the values of the material gain. This means that the giant modal gain comes from the slowing down of the average energy propagation. A slowed energy transport allows more energy exchange events between waves and gain/loss media, or a slow wave will experience more absorption or emission events than fast wave when traveling through the same distance. If the total system is lossy, this enhanced exchange will lead to large modal loss near resonance; similarly in the opposite situation, it will lead to a huge modal gain. At the SPP resonance, the slowest energy velocity ($\varepsilon_1''=-0.4$) is about 200 m/s. This is a factor of 1.5 million slowing down compared to the speed of light in vacuum. Such a dramatic slowing down allows much longer interaction time per unit propagation length so that any small modal gain increases to a giant value.

While the enhancement of modal gain is obviously of great significance, this only occurs when the material gain is sufficiently large to balance out the metal loss and to achieve such a huge modal gain. It is thus important to assess the feasibility of such material gain. For example, in order to obtain the giant modal gain in the MSM waveguide with 100-nm-thick middle layer, the required minimum material gain ($G_{\min}$) is about 1.34×10^4 cm^{-1} (corresponding to $\varepsilon_1''\approx-0.396$). While material gain of this magnitude or as large as 2×10^4 cm^{-1} has been shown possible in wide-gap semiconductor quantum wells such as nitrides or II–VI semiconductors,[14] it is more desirable to have this gain enhancement occur at a lower material gain level. A possible initial experiment can be performed at low temperature. As is well known, optical loss in metals such as silver is significantly reduced at low temperature while gain in semiconductor is significantly increased. It was shown experimentally that the imaginary part of silver dielectric constant is reduced as temperature decreases.[15] The reduction rate at 3 eV is about 5×10^{-4} K^{-1}. Groeneveld *et al.*[16] theoretically estimated the temperature coefficients of both real and imaginary parts of silver dielectric constant at 2 eV to be 8.5×10^{-4} and 1.5×10^{-3} K^{-1}, respectively. Using the experimental results of Ref. 15, we estimate that the required imaginary part of the semiconductor dielectric constant can be as low as -0.271 at 77 K to achieve the giant modal gain, corresponding to a material gain of 9×10^3 cm^{-1}. To be more specific, we considered a MSM waveguide with $Zn_{0.8}Cd_{0.2}Se$ as the middle layer material at 77 K. We calculated the material gain of $Zn_{0.8}Cd_{0.2}Se$ via a free-carrier model,[14] using material parameters of ZnSe and CdSe in Ref. 17. The material parameters of $Zn_{0.8}Cd_{0.2}Se$ were obtained by linear interpolation. The calculated gain G_0 spectrum is shown in Fig. 3 (dash-dotted line) with carrier density 1.1×10^{19} cm^{-3}. Such a gain level at 77 K is reasonable in $Zn_{0.8}Cd_{0.2}Se$.[18] The actual spectral dependence of imaginary part of the dielectric function obtained using $\varepsilon_1''=-ncG_0/\omega$ is then used to solve for the propagation wave vector, k_z, which is shown for the fundamental TM mode in Fig. 3 (solid line). As we see, a huge negative imaginary k_z (dashed line) occurs near SPP resonance, meaning the giant modal gain occurs in this more realistic case. In addition, this specific example also justifies our earlier treatment of imaginary part of the dielectric function of the semiconductor as a frequency-independent value, since semiconductor gain is much broader than the imaginary part of the wave vector near SPP resonance.

To summarize, we have investigated interaction between photons and plasmons near the SPP resonance in a MSM plasmonic waveguide. We discovered a rather unusual phenomenon, i.e., the existence of a giant modal gain near the SPP resonance that is more than 1000 times the material gain of the semiconductor. Since the real part of k_z is maximum

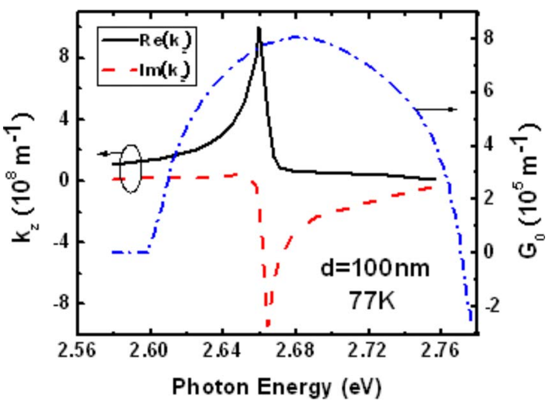

FIG. 3. (Color online) Real (solid) and imaginary (dash) part of k_z for the fundamental TM mode of silver/$Zn_{0.8}Cd_{0.2}Se$/silver waveguide with $d=100$ nm at 77 K. G_0 (dash dot) in the $Zn_{0.8}Cd_{0.2}Se$ layer was calculated at carrier density 1.1×10^{19} cm^{-3}.

(or, the effective wavelength is minimum) near the SPP resonance, devices operating near SPP resonance can be made the smallest in size. The discovery of this giant gain will make it possible to achieve both positive gain and smallest size simultaneously, necessary features of nanophotonic devices. We also identified the physical origin of this giant gain and attributed it to the dramatic slowing down of energy velocity to as slow as 200 m/s. This realization will contribute significantly to our rapidly increasing understanding of SPP phenomena in active plasmonics and will likely to stimulate experiments to search for such giant gain. As a first experiment, we suggest a MSM waveguide with grating coupling for the incident light to excite SPP. In a MS structure, pumping can be incident from the semiconductor side and the SPP can be excited through spontaneous emission. In reality with long propagation length, nonlinear saturation could be also important both inside semiconductor and inside metal. All these issues need to be examined. In addition, amplified or long propagating SPPs will enable many experiments and will greatly impact many areas of physics such as condensed matter, classical and quantum optics, and metamaterials. Finally, such unprecedented modal gain is also expected to have great impact to many plasmonic devices such as plasmonic waveguides for future on-chip interconnects, subwavelength sources such as SPASERS, and many other truly nanophotonic devices.

This work was supported by the Defense Advanced Research Project Agency (DARPA) program Nanoscale Architectures of Coherent Hyper-Optical Sources (NACHOS).

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