Ultracompact beam splitters based on plasmonic nanoslits

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An ultracompact plasmonic beam splitter is theoretically and numerically investigated. The splitter consists of a V-shaped nanoslit in metal films. Two groups of nanoscale metallic grooves inside the slit (**A**) and at the small slit opening (**B**) are investigated. We show that there are two energy channels guiding light out by the splitter: the optical and the plasmonic channels. Groove **A** is used to couple incident light into the plasmonic channel. Groove **B** functions as a plasmonic scatterer. We demonstrate that the energy transfer through plasmonic path is dominant in the beam splitter. We find that more than four times the energy is transferred by the plasmonic channel using structures **A** and **B**. We show that the plasmonic waves scattered by **B** can be converted into light waves. These light waves redistribute the transmitted energy through interference with the field transmitted from the nanoslit. Therefore, different beam splitting effects are achieved by simply changing the interference conditions between the scattered waves and the transmitted waves. The impact of the width and height of groove **B** are also investigated. It is found that the plasmonic scattering of **B** is changed into light scattering with increase of the width and the height of **B**. These devices have potential applications in optical sampling, signal processing, and integrated optical circuits. © 2011 American Institute of Physics. [doi:10.1063/1.3582005]

I. INTRODUCTION

A beam splitter is an optical device for splitting a light beam to several beams.^{1–8} It is an important optical device in many practical applications including optical signal sampling,¹ laser splitting,^{2–4} and interferometers.^{5,6} The conventional beam splitters are made of prisms,⁷ gratings,^{4,6} and optical binary structures.⁸ These devices are based on the optical interference principle. They usually have large dimensions and complex structures. Here, we propose a method for modulating collimation and transmission intensity of the light beams through the use of a plasmonic nanoslit.^{9–12} Compared with conventional beam splitters, the plasmonic nanoslit is smaller, and it can be readily integrated into more complex devices. Furthermore, the transmission energy and diffractive patterns are easily modulated by controlling the plasmonic parameters. The proposed beam splitter may find potential applications in integrated optical circuit, optical signal sampling, and data processing.

Surface plasmon polaritons (SPPs) are electromagnetic waves that interact with the longitudinal oscillation of free electrons along the surface of a metal.^{13–18} The high confinement and localization of SPPs provides an efficient way to greatly enhance the electromagnetic intensity in a very small region, hence the intensive energy effects such as optical nonlinearity are easily excited.^{13,14} Furthermore, it offers an easy way to manipulate light at nanoscale beating the diffraction limit of light.^{15,16} So far, there are many ultracompact optical devices based on SPPs proposed and demonstrated in the literature.^{9–18} Among them, nanopores and nanoslits are widely utilized because they can provide enhanced transmission and beam directional properties with

the aid of surface plasmons.^{9–12,18} In this paper, we investigate nanoscale structures to tailor the surface plasmon modes sustained by a thin metal coating for coupling light into and out of the nanoslit punched in the metal. We demonstrate that the transmission through a metal nanoslit present in a V-shape groove can be greatly enhanced by introducing nanostructures in the nanoslit and around the small opening of the nanoslit (Fig. 1). The numerical results using finite-difference time-domain (FDTD) show that the transmission is enhanced >10–12 times by adopting these nanostructures and that the divergent angle of transmission is also greatly suppressed. Furthermore, different beam splitting effects can be achieved by simply changing the interference condition between the SPP waves and the light transmitted through the slit.

II. THEORETICAL DESCRIPTION

SPPs are quasiparticles that consist of surface photons and surface plasmons. These surface photons and surface plasmons interact with each other. They are complementary in nature: on the one hand, the surface photons are excited by the oscillation of surface plasmons; on the other hand, the surface photons will induce surface charges and drive these charges to oscillate, becoming “surface plasmons.” However, the SPP modes are not decided by specific surface photons and plasmons. Given a metal material, the SPP modes can be determined using following expression:

$$k_{\text{spp}} = \frac{\omega_0}{c} \sqrt{\frac{\epsilon_m \epsilon_0}{\epsilon_m + \epsilon_0}} \quad (1)$$

where k_{spp} is the SPP wave vector parallel to the conductive surface; ω_0 is the resonant frequency of light, and c is the speed of light; ϵ_0 and ϵ_m are dielectric constants of

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FIG. 1. (Color online) Schematic of a SPP nanoslit. (a) is a three-dimensional SPP nanoslit impinged by a white light on the big opening side. The incident light is coupled, filtered, and enhanced by the SPP device, becoming transmitted light with narrowband, enhanced intensity, and suppressed beam divergence. (b) is the side view of the nanoslit, where H and D are the height and distance of the structure **B**. w_1 and w_2 are the width of the bump and groove, respectively. h is the thickness of the metal. a_1 and a_2 are the length of the large and small openings of the nanoslit, respectively.

surrounding and metal medium, respectively. ϵ_m is usually complex with a negative real part for metallic material. So, k_{spp} is also a complex; the imaginary part of which corresponds to the absorption loss of energy by the metal. The imaginary part of k_{spp} constrains the propagation distance of the SPPs along a metallic surface.

There are two approaches to excite the SPP waves: by light or by electron excitation. In practice, the light excitation for SPP generation is the most easily adopted. A large body of data is available on the excitation of SPP waves in the literature.^{9–18} Because the SPP oscillation has its own orientation, it is required that the excitation light possesses certain polarization to match the oscillation direction. Transverse magnetic (TM) polarized light has an electric component perpendicular to the metal surface that can induce and dynamically hold charges on the surface, so it can be used to excite SPP waves. Furthermore, to excite a SPP wave, the external light should have the same oscillation frequency ω_0 that of SPP, and a wave vector component matching k_{spp} . However, because ϵ_m is negative for metal, this leads to $k_{\text{spp}} > k_0$

($k_0 = \omega_0/c$). Considering $k_0 = \sqrt{k_{\perp}^2 + k_{\parallel}^2}$, where $k_{\perp}$ and $k_{\parallel}$ are wave vector components of incident light perpendicular and parallel to the surface, $k_{\perp}$ is imaginary because $k_{\parallel} = k_{\text{spp}}$. The latter condition implies that the incident waves are evanescent along the normal direction of the metallic surface.

For achieving large $k_{\parallel}$, many schemes were proposed including prisms, gratings, nanoslits, ridges, and bumps in metallic surface. The coupling light to SPPs can be classified into two categories: one type of devices directly generate evanescent waves by matching k_{spp} with one component of wave vector based on total inner reflection (prisms) or scattering (nanoslits, ridges and bumps). Another set of devices use periodic structures (grating) to excite Bloch waves, and the resonance between SPP and optical Bloch wave occurs as k_{spp} matches with Bloch order,

$$k_{\text{spp}} = k_{\parallel} + nG \quad (2)$$

where n is any integer and G is the reciprocal lattice vector ($G = 2\pi/T$, and T is period of grating). The prisms are too big for miniaturization, and their integration into microelectronic or micro-optical devices is specially prohibited for many practical applications. The nanoslits, bumps, and ridges suffer from the low coupling rate of energy between light and SPPs. In this paper, we use periodic structures to couple the light in and out of the SPP device based on V-shaped grooves containing nanoslits.

III. STRUCTURE DESCRIPTION AND NUMERICAL MODEL

The SPP device we proposed consists of a V-shaped nanoslit (Fig. 1). The nanoslit has a V-groove cross-section (in the x - y plane) and infinite dimension along z axis. Two kinds of nanostructures are used for coupling the light to SPPs. One nanostructure is presented inside of the slit called structure **A**, and another structure is presented at the small slit opening called structure **B**. The nanoslit can be fabricated from a metallic slab (such as gold, silver, chromium, etc.) or consists of a metal coating on top of a dielectric slit (for example, glass). The thickness of metal is $h = 10 \mu\text{m}$ and permittivity $\epsilon_m = -8.55 + i8.95$ (of chromium) at wavelength $\lambda = 630 \text{ nm}$ is chosen for our calculations in these studies. The large and small openings of the nanoslit are chosen to be $a_1 = 5.29 \mu\text{m}$ and $a_2 = 222 \text{ nm}$, respectively. The nanostructures **A** and **B** are used to couple the light into and out of the SPP modes (Fig. 1). Structure **A** consists of alternative hemicylinders inside of the nanoslit with period $T = 316 \text{ nm}$ and radius $r = 158 \text{ nm}$. Structure **A** acts a wavelength filter and an energy coupler. Structure **B** functions as an energy coupler to separate light out from the SPP modes and beam the light out of the slit. Structure **B** consists of several rectangle grooves around the small opening of the slit, where the widths of the bumps and the grooves are $w_1 = 95 \text{ nm}$ and $w_2 = 405 \text{ nm}$, and the height $H = 80 \text{ nm}$ (Fig. 1). The distance separates the two parts of **B** is $D = 538 \text{ nm}$. Owing to the groove structures, the phase matching conditions for sustaining SPP modes are broken, so the light and the electrons are separated. The light is scattered and coupled into the radiation modes supported by the groove structures.

Based on a FDTD program, we simulated the transmission of a TM-polarized light passing through the nanoslit. We adopted the Drude model to simulate the metallic permittivity,

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - i\Gamma)} \quad (3)$$

where ω_p is the plasma frequency of the metal and Γ is the damping frequency due to the collision and Doppler broaden. In our calculation, we assume $\omega_p = 1.26 \times 10^{16}$ Hz and $\Gamma = 2.79 \times 10^{15}$ Hz to fit the chromium permittivity into the visible region, especially $\varepsilon_m = -8.55 + i8.9$ at the SPP wavelength $\lambda = 630$ nm.

IV. RESULTS ANALYSIS AND DISCUSSION

A. Roles of structures *A* and *B*

In Fig. 2(a), the transmission distribution of light passing through a bare nanoslit is presented. The numerical calculation shows only 1.6% light energy transmits from the slit [Fig. 2(d)], and the transmitted light is scattered uniformly in the whole transmission space. The uniform distribution of the transmission is ascribed to the subwavelength size of slit. The transmission from such small slit can be treated as an emission from a Huygens' secondary point source that emits a spherical wave uniformly distributed in the space. On the metal surface, we observed the SPP waves were excited through the edge of metal slit. The SPP waves are nonradiative in nature because there is no mechanism to separate the surface photons from the SPP waves (except at the metal edges where the SPP conditions are broken). We then investigated the nanoslit with structure *B* only and the presence of both *A* and *B*. The transmission distributions for these two

cases are shown in Figs. 2(b) and 2(c), respectively. By adopting *B*, the transmission output integrated intensity is increased by ~ 10 times as compared to the bare nanoslit case. Furthermore, the scattering divergence is greatly suppressed. By using both *A* and *B*, the light transmission intensity is further enhanced to ~ 12 times than that for the bare case.

B. Transmission spectrum of structure *A*

As the light impinges on the SPP device, there are two paths guiding the light out of the slit, i.e., the conventional optical transmission path from slit and the plasmonic path guided by the surfaces inside of the slit. For the former path, the transmission is mainly determined by the size of the small opening of the slit. Given a slit, the transmission through optical path is decided. The plasmonic path provides a new energy transfer channel to enhance the transmission. Structure *A* is designed to couple light energy into the SPP modes. Structure *A* consists of alternative hemicylinders inside of the slit wall. The period T of the alternative hemicylinders are designed to satisfy Eq. (2) at wavelength $\lambda = 630$ nm. The length of *A* is important to the phase of the plasmonic waves. We optimized the length of *A* to enhance the transmission. To investigate the transmission enhancement by structure *A*, a Gaussian TM pulse with duration 15 fs and central wavelength $\lambda = 630$ nm is designed to penetrate the SPP device based on a FDTD program. By recoding the incidence at plane 1 and the transmission at plane 2 [Fig. 2(a)], the integrated transmission spectrum is achieved [Fig. 2(d)]. For comparison, we also present the transmission curves for the bare slit and the slit with *A* and *B* structures present in it. For the bare one, the integrated transmission energy is about 1.6% at $\lambda = 630$ nm, but it is enhanced to 2.8% by using *A*. It is demonstrated that dominant

FIG. 2. (Color online) Intensity distributions of the SPP nanodevices. (a) is a bare V-shape nanoslit in a piece of metal, where planes 1 and 2 are the integrated intensity planes for calculating the integrated transmission spectrum. (b) and (c) correspond to the transmission of nanoslit with structure *B* and both *A* and *B*. The inset shows the magnified detailed nanostructures. (d) shows the transmission spectra for a bare nanoslit, a slit with *A*, and a slit with *A* and *B*, respectively.

mechanism of energy transfer is plasmonic path in nature. We also noticed that the integrated transmission energy for the slit with **A** and **B** is 6.8%. It is clear that the integrated transmission energy has been greatly enhanced by using structures **A** and **B**. Therefore, structure **A** couples more energy into plasmonic channel, while structure **B** couples the plasmonic energy out and squeezes the energy to some narrow regions through interference with the light from the slit.

C. Truncation effects of structure **B**

At the edge of nanoslit, SPP waves are excited and propagating along the metal surface. Structure **B** blocks the propagation of the waves along the parallel to the surface (at bottom of the small opening of the slit), and it transfers SPP energy into light waves. Therefore the structure **B** effectively extends the size of nanoslit leading to significant transmission increase. The slit broadening reduces the diffraction effect, explaining the suppressed scattering beam divergence. Our calculations suggest that the preceding results can be provided by a pair of grooves [Fig. 3(a)], where a large divergent angle of beam is observed. As the number of grooves increase, we found that the transmission divergence is greatly suppressed [Figs. 3(b) and 3(c)]. The divergence suppression can be regarded as a low-pass filter effects. Mathematically, for a finite size periodic structure, the field can be expressed by

$$H(x, z) = u(x, z)e^{iGx} \otimes \text{rect}(x/a) \quad (4)$$

where $\otimes$ is convolution operator and $\text{rect}(x/a)$ is a window function (low-pass filter). In the spatial frequency domain, it corresponds to a truncation of the Bloch orders. Because higher order harmonics are excluded by the truncation, it leads to a decrease in transmittivity and broadens of the transmission beam.

D. Impact of the spacing distance H on structure **B**

Structure **B** also controls the phase of the scattered light. By altering the distance H of structure **B** in the slit, we investigated the diffraction patterns in the output light. Because the slit and the structure **B** have subwavelength dimensions, the transmitted light can be simply regarded as the Huygens' point sources. The diffraction patterns are then treated as the interference of these three sources (slit and two parts of **B** divided by slit). Therefore, the transmission magnetic field H_z is expressed by,

$$H_z(x, z) = H_0(z)e^{ik_x x} + \gamma H_0(z)e^{ik_{\text{spp}} \frac{H}{2}} e^{ik_x (x + \frac{H}{2})} + \gamma H_0(z)e^{ik_{\text{spp}} \frac{H}{2}} e^{ik_x (x - \frac{H}{2})} \quad (5)$$

where H_0 is the magnetic field at the small opening of the slit; $k_x = k_0 \sin \theta$, θ is transmission angle, and $k_0 = 2\pi/\lambda_0$; γ is the SPP coupling coefficient of structure **B**.

Equation (5) can be further simplified as $H_z(x, z) = H_0(z)e^{ik_x x} [1 + \frac{1}{2}\gamma H_0(z) \cos(k_x \frac{H}{2}) e^{ik_{\text{spp}} H/2}]$, suggesting that the amplitude of the scattering field is modulated by $\cos(k_x \frac{H}{2})$, and the phase is determined by $e^{i(k_{\text{spp}} \frac{H}{2})}$. Thus the conditions of the constructive interference are:

FIG. 3. (Color online) Intensity distribution of SPP nanodevices with different size of structure **B**. (a), (b), and (c) are plotted to show the divergence suppression by using different number of grooves $N = 1, 3$, and 10 .

$k_{\text{spp}} H/2 = 2\pi n$ and $k_x H/2 = 2\pi m$, where n and m are integers. Combining and solving the preceding two conditions, we have $\sin \theta = \frac{n/m}{\lambda_0} \lambda_{\text{spp}}$, and the diffraction order m is given by,

$$m = \left\lfloor n \frac{\lambda_{\text{spp}}}{\lambda_0} \right\rfloor + 1 \quad (6)$$

where $\lfloor \cdot \rfloor$ means rounding to minimum integer. Because λ_{spp} is approximately equal to λ_0 , Eq. (6) implies $m \sim n + 1$. In Figs. 4(a)–4(d), the transmission intensities of the device with different spacing of **B** are presented. The spacing lengths are $H = 1.03\lambda_{\text{spp}}$, $2.06\lambda_{\text{spp}}$, $3.09\lambda_{\text{spp}}$, and $4.11\lambda_{\text{spp}}$, respectively. These spacing values correspond to the diffraction orders $m = 2, 3, 4$, and 5 , respectively. These numerical values of H are consistent with our theoretical estimation. Therefore different beam splitting effects can be achieved by simply changing H .

FIG. 4. (Color online) Intensity distribution of SPP nanodevices with different length D of structure **B**. (a) - (d) correspond to the structure **B** with $H = 1.03\lambda_{\text{spp}}$, $2.06\lambda_{\text{spp}}$, $3.09\lambda_{\text{spp}}$, and $4.11\lambda_{\text{spp}}$, respectively.

E. Effects of groove width of in structure **B**

Structure **B** can be regarded as a defect in the flat metallic surface. As the SPP waves pass through it, the SPP waves will experience the perturbation from the defect. If the groove of **B** is sufficient narrow such that $w_2 \ll \lambda_{\text{spp}}$, it corresponds to a weak perturbation in the flat metallic surface. The SPP mode maintains its propagation on the surface except along the grooves, where SPP waves are scattered and the energy is coupled to a light mode in free space. For a device with $w_2 = 32$ nm, we observed that the SPP mode is strongly excited on the metallic surface, and the light beams are emitted in different directions by these grooves. To study the effects, we investigate the magnetic field distribution along the metallic surface. We observed that the SPP mode maintains its distribution on the surface, whereas the field in

the groove takes opposite phase against the SPP waves [Fig. 5(b)]. The sudden change of phase in the groove can be understood due to maintenance of zero magnetic fields on the surface where no free charges are present. Due to lack of surface charges, the light cannot be bounded to the surface; therefore it couples out to the free space. We also noticed that each groove corresponds to different phase of SPP waves. These different phases determined the scattering direction from different grooves.

If the grooves are wider, the perturbation is strong, and the SPP modes are not able to keep its propagation any more. In Fig. 5(c), the transmission intensity for the device with $w_2 = 348$ nm is presented. We observed that largest SPP energy is scattered out by the first groove edge, and the intensity along the groove vector is decayed very fast. We also investigated the magnetic field distribution along the metallic surface with grooves [Fig. 5(d)]. For the wider grooves, a new energy transfer along metal surface occurs instead of SPP. The SPP waves interact with the first pitch, and it induces opposite charges on the two sides of the pitch. Then the charges on the first pitch induce opposite charges on the second pitch. By following this way, the energy is transferred along the structure **B**. We can confirm this energy transfer in Fig. 5(d) in which opposite magnetic fields are induced on the two sides of each pitch. In this case, the SPP modes totally disappear, and each groove works like a cavity. Because the induced light in each groove is not fit for a cavity mode, it decays very fast along the grooves, leading to the scattering of energy in the free space. If the incident light matches one of the cavity modes, the light energy will be coupled into the cavity mode, corresponding to a guided mode resonance.

F. Effect of groove height of structure **B**

The height D of structure **B** also plays an important role in the formation of the transmission patterns. To simplify the analysis, we consider a device with only three grooves and analyze the effect of D on the light transmission. Because the first groove dominates the scattering fields, it is sufficient to focus our investigation on the fields in the first groove.

For a short **B** ($D < \lambda_{\text{spp}}$), the SPP waves definitely dominate the scattering. In Fig. 6(a), the transmission pattern of a device with groove length $D = 4.11\lambda_{\text{spp}}$ and height $H = 396$ nm is present. We observed that there are four diffraction orders formed [Fig. 6(a)]. The diffraction pattern is similar to that in Fig. 4(c), which has the same structure but possesses a lower height D . The corresponding magnetic field is shown in Fig. 6(d). We observe SPP waves are excited by the edges of small openings, and then they propagate along the bottom of the first groove. This is followed by scattering of the SPP waves at the two pitches. The total field is decided by the interference of the SPP scattering light and the transmission light from nanoslit.

However, for a high **B** ($D > \lambda_{\text{spp}}$), the SPP energy is localized within the bottom of the groove, and the light guided modes are formed above the SPP region in the groove. It is the guided modes in the groove that dominates the diffraction patterns instead of SPP waves. We also

FIG. 5. (Color online) Transmission of the SPP nanodevices with different groove widths w_2 . (a) and (c) are the intensity and magnetic field distribution for $w_2 = 32$ nm, and (b) and (d) are distribution for $w_2 = 328$ nm.

FIG. 6. (Color online) Transmission of the SPP nanodevices with different groove height D . (a) and (d) are the intensity and magnetic field distribution $D = 32$ nm, (b) and (e) are distribution for $D = 328$ nm, and (c) and (f) are distributions for $D = 328$ nm.

investigated the transmission of the same device with larger height $D = 1.16\lambda_{\text{spp}}$ and $2.19\lambda_{\text{spp}}$. The intensity distributions are shown in Figs. 6(b) and 6(c), respectively. The two cases have five diffractive orders, which are different from Figs. 6(a) and 4(c). In Figs. 6(e) and 6(f), the magnetic fields of transmitted light waves are shown. We observe that the SPP mode is largely confined in the bottom of groove, and new guided modes are formed above the SPP standing waves. The complex transmission patterns result from the multiple guided modes interference in the groove. Because these guided modes are decided by the width of the waveguide, the diffractive orders remain the same with different height D , but their intensity distributions are different due to different coupling efficiency. As the groove length H decreases, the confinement of the groove is enhanced so the guided modes are easily formed even with a very low height D . In this case, the SPP modes and guided modes will entangle together, so the diffraction patterns are much more complex with the increase of D .

V. SUMMARY

We theoretically and numerically investigated the transmission of a light passing through a V-shaped nanoslit punched in a piece of metal. Two groups of nanostructures **A** and **B** are designed inside the slit and at the small slit opening. We demonstrated that the plasmonic energy transfer to light energy is dominant for a nanoslit. More than four times the energy is transferred by the plasmonic channel using structures **A** and **B** than nanoslits without structure in them. We also investigated the scattering of plasmonic waves. It is shown that the scattering light waves redistribute the transmitted energy by interference with the field transmitted from the nanoslit. Therefore different beam splitting effects are achieved by simply changing the interference conditions between the SPP waves and the transmitted light waves. The

impact of the width and height of groove **B** are also investigated. It is found that the plasmonic scattering of **B** is changed into light scattering as the width and the height of **B** increases. The devices have potential applications in optical sampling, signal processing, and integrated optical circuit.

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