Optical Waveguide Beam Splitters Based on Hybrid Metal-dielectric-semiconductor Nanostructures

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Abstract: Miniature integration is desirable for the future photonics circuit. Low-dimensional semiconductor and metal nanostructures is the potential building blocks in compact photonic circuits for their unique electronic and optical properties. In this work, a hybrid metal-dielectric-semiconductor nanostructure is designed and fabricated to realizing a nano-scale optical waveguide beam splitter, which is constructed with the sandwiched structure of a single CdS nanoribbon/HfO₂ thin film/Au nanodisk arrays. Micro-optical investigations reveal that the guided light outputting at the terminal end of the CdS ribbon is well separated into several light

spots. Numerical simulations further demonstrate that the beam splitting mechanism is attributed to the strong electromagnetic coupling between the Au nanodisks and light guided in the nanoribbon. The number of the split beams (light spots) at the terminal end of the nanoribbon is mainly determined by the number of the Au nanodisk rows, as well as the distance of the blank region between the nanodisks array and the end of the CdS ribbon, owing to the interference between the split beams. These optical beam splitters may find potential applications in high-density integrated photonic circuits and systems.

Keywords: metal-dielectric-semiconductor; optical waveguide beam splitter; surface plasmons; interference; light spot; numerical simulation

1. Introduction

Recently, Miniaturization of optical components or devices is necessary in developing integrated photonic circuit, which has led to the great advances in developing various compact optical elements, such as nanolasers [1-4], optical switching [5] and filter [6]. Beam splitter in the nano-micro scale is one of the key elements for photonic circuits, and is commonly used in many kinds of optical systems for optical information processing, optical computing, holography, and metrology [7-15]. Surface plasmons (SPs), a coherent oscillation of the surface conduction electrons excited by electromagnetic radiation, has series of special optical properties, including sub-wavelength confinement of light, electromagnetic enhancement and polarization sensitivity [16-24]. For these particular properties of SPs, low dimensional noble metal nanostructures, for example, nanoparticles,

nanowires and nanofilms, have enabled a vast array of applications, including surface-enhanced spectroscopies, biological/chemical sensing, and optical information processing [25-29]. However, optical information transferred by SPs is not an ideal candidate owing to the large intrinsic ohmic damping of the metal [30]. Fortunately, one-dimensional (1D) semiconductor nanostructures, are not only promising building blocks in assembling compact optical elements, but also the bridging of the nanoscopic and macroscopic world, for their unique optical properties and high-aspect-ratio [31-36]. Comparing with other dimensional nanostructures such as quantum dot and thin film, 1D semiconductor nanostructure (nanowires/nanoribbons) is easier to be manipulated and can offer a more excellent platform for tight confining and guiding light at sub-wavelength scale in one dimension, because they can confine photons in two dimensions and let the light propagate freely in the third dimension [37-40]. CdS nanoribbon is an optimal waveguide cavity for its rectangular cross section with a well-defined geometry, relatively high refractive index and flat surface [41]. Additionally, due to the high luminous efficiency, the light emitted from the CdS nanoribbon can be directly guided in the ribbon, which makes the waveguide avoid the light coupling. Utilizing the strong electromagnetic coupling between the optical waveguide in the 1D semiconductor nanostructures and low dimensional noble metal nanostructures to induce SPs can give rise to abundant optical properties and even create a new path to invent better-performance optical elements [42-45]. Here, we designed and fabricated a novel sandwich-like hybrid nanostructure for the first time, which composed by Au nanodisks array covering on a CdS nanoribbon, with a thin

HfO₂ film as the intermediate dielectric layer. Due to the electromagnetic coupling of SPs and optical waveguide in the nanoribbon, the guided light in the ribbon can be isolated and separated by the Au nanodisks array rows. Meanwhile, the increase of blank region distance between the nanodisks array and the terminal end of the CdS ribbon results in the multi-beam interference in the nanoribbon. The number of the split beams (light spots) is determined by the row number of the Au nanodisk array and the distance of the blank region between the Au nanodisk arrays and the ribbon end. For construction of a novel optical waveguide beam splitter at nano/micro-scale, these results may take a significant step toward the goal and find a new way to realize small footprint photonic circuits.

2. Fabrication

In this study, CdS nanoribbons with length of several tens micron and width of several micron were synthesized through a chemical vapor deposition (CVD) route as previously reported in the literature [46]. Si/SiO₂ (thickness of SiO₂ is 200 nm) substrate with markers patterned lithographically, which is commonly used in electron-beam lithography (EBL), was cleaned with acetone. Then, some nanoribbons were individually removed from the original grown substrate and transferred onto the pre-cleaned Si/SiO₂ (200 nm) substrate via homemade micromanipulation technique [47], following which a dielectric cladding of HfO₂ (15 nm thick) was deposited on the dispersed nanoribbons through atomic layer deposition (ALD) method. Finally, Au nanodisk arrays (thickness ~50 nm) were fabricated on some nanoribbons by EBL

(JOEL, JSM-6510) using a standard liftoff procedure [48]. A representative hybrid nanostructure is schematically described in Fig. 1(a).

3. Morphology characterization and optical measurement

Fig. 1(b) is the scanning electron microscopy (SEM) image for a representative hybrid nanostructure with three rows Au nanodisk array along the length of the ribbon, which shows that Au nanodisks, with nearly the uniform diameter of ~ 300 nm, were aligned on the CdS nanoribbon into three rows. Fig. 1(c) gives the Atomic Force Microscopy (AFM) image of the sample same as in Fig. 1(b). The further analysis of the AFM results with cross section profile (see Fig. 1(d)) along the marked line in Fig. 1(c) indicates that the thickness of the CdS nanoribbon and Au nanodisk is ~ 100 nm and ~ 48 nm, respectively.

The photoluminescence (PL) spectra and optical waveguide were conducted on a Confocal Microscope (Witec α -SNOM 300), locally excited with a 488 nm laser (Ar⁺ laser). Fig. 2(a) shows the representative PL spectrum of bare CdS nanoribbons. The single band emission with the peak wavelength at 510 nm is consistent with the band-edge emission of CdS at room temperature, which indicates the high quality of the CdS nanoribbon. Fig. 2(b) and (c) give the dark field optical micrographs of a bare CdS nanoribbon respectively under wide illumination of tungsten lamp and local excitation of 488 nm laser. Except for the light spot emitted from the excited point, the light can be guided to and emits from the end of the ribbon, which presents a monolithic rectangular light strip at the right end (see the amplified image of the white line marked area in Fig. 2(c)). This is due to the high refractive index contrast between

the nanoribbon and surroundings, the nanoribbon can function as a rectangle optical waveguide cavity, in which light can be well confined and guided along its length direction. According to the waveguide theories, the evanescent wave should exist on the surface of the waveguide nanoribbon, and hence interacts with the Au nanodisks fabricated on the ribbon. Fig. 2(d) shows the dark field optical micrograph of a CdS nanoribbon with two rows of Au nanodisks array under the wide illumination of tungsten lamp, from which the individual Au nanodisks can be distinguished. Comparing with the bare CdS nanoribbon, under locally excitation with focused 488 nm laser, the ribbon with two rows of Au nanodisks shows three unambiguous light spots at its terminal end isolated with two dark regions just corresponding to the position of the Au nanodisk rows (see the right end in Fig. 2(e)). The number of the waveguide light spots at the end of CdS nanoribbon can be tuned by varying the number of the Au nanodisks array rows. Fig. 2(f) shows the dark field image of the CdS nanoribbon with three rows of Au nanodisks under wide illumination, and the corresponding optical image with focused laser excitation is given in Fig. 2(g). Four light spots can be clearly observed, and isolated by three dark region at the position corresponding the Au rows. Therefore, we conclude that the Au nanodisks rows on CdS nanoribbon can split the waveguide light beam, which is attributed to the interaction between Au nanodisk arrays and the guided light in the ribbon.

4. Simulations and discussion

To obtain further insight into the light-matter interaction mechanism in this novel nanostructure, numerical simulations were carried out using the finite element method

[6,49]. Herein, basing on the size of the fabricated sample, we build a 3D model of the hybrid nanostructure with two rows of Au nanodisks array on the CdS nanoribbon, where a z-axis polarized light of 510 nm was launched from one end of the ribbon [50]. The theoretical model is based on the equation: $\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \epsilon_r \mathbf{E} = 0$ [51], where $\mathbf{E}$ is the electric fields of the optical field and the complex relative permittivity $\epsilon_r = \epsilon'_r + \epsilon''_r = (n + ik)^2$ is determined by the refractive index n and the extinction coefficient k of the material, with real and imaginary parts ϵ'_r and ϵ''_r . $k_0 = \omega / c$ is the free space wave number, ω is the angular frequency, c is the speed of light in vacuum. The material of each part of the nanostructure was defined by the wavelength dependent n and k . n of CdS nanoribbon, HfO₂ dielectric layer and Au nanodisks are 2.82, 2.11 and 0.75, respectively, and k of Au was 1.92. For illustrating the optical splitting mechanism of the hybrid nanostructure qualitatively, we provide the calculated results of the simplified simulation model without containing the substrate and set the surrounding medium of the nanostructure as air ($n=1$). Fig. 3(a) is the volume electric field (E-field) distribution at the surface of the simulated structure, three maximum E-field regions along the length of the ribbon are observed, which are isolated by two dark regions just corresponding to each row of the Au nanodisks. This can be further proved by the cross section profile analysis for the down end of the ribbon (see inset of Fig. 3(a)), as well as the mode profiles of x-z and y-z plane are shown in Fig. 3(b). Especially, the mode profile of y-z plane in bottom of Fig. 3(b) shows that the maximum E-field distributes at the regions without Au nanodisks, and the minimum one is in the ribbon under the Au nanodisks, which clearly demonstrates

surface attached Au nanodisks absorb the guided light beneath it in the nanoribbon. Fig. 3(c) shows the surface charge density distribution simulation image of one representative Au nanodisk, which indicates the charge at the surface of Au nanodisk is polarized. Surface plasmons are generated from the interaction between the light wave trapped at metal surface and free electrons in the metal [52, 53]. Here, the HfO_2 thin film was used as the spacer to avoid the detrimental effect of nonradiative surface trap states caused by the Au nanodisks on the CdS nanoribbon, which offers the opportunity to investigate the intrinsic properties of the CdS ribbons [54, 55]. Additionally, because of the sub-wavelength size and the relative large interval of Au nanodisks, plasmons can not propagate along the metal-dielectric interface but oscillate locally around the Au nanodisks, which is so called localized plasmon (LSP) [56]. Therefore, the light guided in the nanoribbon is trapped by the Au nanodisks, which results in the collective oscillation of free electrons. Due to the scattering loss and inherent ohmic damping of the metal, much of the absorbed energy is dissipated in these Au nanodisks. As a result, it is reasonable to believe that the propagating light through the areas covered with Au nanodisks will be absorbed by Au arrays, by which Au arrays isolate the light propagated in the nanoribbon.

To such a nanostructure, optical waveguide in the nanoribbon can be considered as several light beams propagating along each sub-wavelength channel (about 300 nm width) isolated by Au nanodisks array. The rule that the number of Au nanodisks array rows plus one equals the number of light beams is obviously manifest by the light-matter interaction mechanism in this nanostructure. Although the light beams are

at sub-wavelength scale, there are both effect of optical diffraction and multi-beam interference similar to Young's interference taken place in the waveguide process [57]. As a result, the number of emitted light spots is not only determined by the number of Au nanodisks array rows, but also by the interference length of multi-beams (distance of the blank region between the nanodisks array and the terminal end of the CdS ribbon, (DC), illustrated in Fig. 4(a₁), (b₁) and (c₁)). Three representative samples that contain same rows of Au nanodisks array with different DC were measured. Fig. 4(a₁) gives the SEM image of one sample which contains three rows of Au nanodisks with DC about 0.45 μm and the corresponding dark field optical image shows that four light spots were emitted at the terminal end of CdS ribbon under locally excitation with focused 488 nm laser (Fig. 4(a₂)). From its corresponding calculated cross-sectional (x-y plane) E-field distribution in the ribbon (Fig. 4(a₃)), it is found that three rows of Au nanodisks have split the guided light into four optical beams, which is due to the DC is not long enough to induce apparent interference and four parted signal output at the terminal of the ribbon. However, for the sample with DC about 1.5 μm (Fig. 4(b₁)), five light spots were emitted at the terminal end of CdS ribbon under locally excitation with focused 488 nm laser (Fig. 4(b₂)). This phenomenon indicates that the DC is long enough for interference between the four split beams, which is proved by its corresponding simulated result (Fig. 4(b₃)). Fig. 3(c) shows the sample with DC of about 2.2 μm , it is found six split light spots emitted at the terminal end of CdS ribbon (Fig. 3(c₂)), and the corresponding simulation results gives the interference pattern resulted from four split light beams

(Fig. 3(c₃)). Therefore, it can be concluded that emitted light spots at the terminal end of nanoribbon is determined by light-matter interaction and the interference of light, which can be used as light splitter in nano-scale optical devices.

From the experimental and simulation results, good splitting ration of the fabricated nanostructure can be inferred from the approximately uniform emit light spots at the end of the nanoribbon and the similar E-field intensity peak values of the three maximum E-field regions (inset of Fig. 3(a)). The equation $\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \epsilon_r \mathbf{E} = 0$ indicates that the E-field intensity distribution in the nanostructure can be modulate by altering the relative dielectric constant of the material: $\epsilon_r = \epsilon'_r + i\epsilon''_r = (n + ik)^2$. Moreover, the imaginary part ϵ''_r concerns the dissipation of energy. There are two parameters, the wavelength dependent refractive index n and the extinction coefficient k , determine the value of ϵ''_r , which equals to $2nk$. The dissipation of energy in metal is a major factor that affects the propagation loss of the splitter. Therefore, choosing the metal which has relative lower value of nk may reduce the propagation loss. Additionally, low refractive index substrates benefit the guided light confining in the device, due to the large refractive index contrast between the waveguide cavity and the substrate.

5. Conclusion

In conclusion, we have designed and fabricated a type of sandwich-like hybrid metal-dielectric-semiconductor optical waveguide beam splitters, which can split the waveguide light into several beams emitting at the end of the CdS nanoribbon. Corresponding numerical simulations demonstrate that waveguide in the nanoribbon

is coupled with the free electrons of the upper Au nanodisks to generate LSP, due to the existence of metal array. This interaction leads to confine and guide light in several sub-wavelength scale channels isolated by Au nanodisks arrays in this nanostructure. The experiment and numerical simulation results reveal that the number of light spots can be tuned by adjusting the number of Au nanodisks array rows and the interference length of the split multi-beams. This kind of nanostructure is a practical high-density optics device and may provide a significant progress for micro/nanoscale optical sensing, logical operation, and communication or compact optical components for integrated nanophotonics.

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Figures

Fig. 1. (a) Schematic of the semiconductor-dielectric-metal beam splitter. A nanodisk array consist of Au cylindrical nanodisks with 300 nm diameter and 50 nm height, a

100-nm-thick CdS nanoribbon and a 15 nm thick HfO₂ layer are plotted from top to bottom. Period of the Au nanodisk array is 600 nm. (b) SEM image of a representative sample (scale bar is 3 μ m). (c) AFM morphological image of the sample (color scale bar indicates the height of the sample from 0 to 170). (d) Cross-section profile plot of the sample along the white dashed line marked in (c).

Fig. 2. (a) The representative PL spectrum of CdS nanoribbons. (b) Dark field optical micrograph of a CdS nanoribbon without Au nanodisks under wide illumination of tungsten lamp. (c) Dark field optical micrograph of the bare ribbon under local excitation of 488 nm laser. (Both of the scale bars are 4 μm). (d) Dark field optical micrograph of a representative sample contains two rows of Au nanodisks array under wide illumination of tungsten lamp (scale bar is 2 μm). (e) Dark field optical

micrograph of the sample under local excitation of 488 nm laser. Inset is the amplified image of the terminal end of CdS nanoribbon (scale bar is 2 μm). (f) Dark field optical micrograph of a sample containing three rows of Au nanodisks array under wide illumination of tungsten lamp (scale bar is 3 μm). (g) Dark field optical micrograph of the sample under local excitation of 488 nm laser. Inset is the amplified image of the terminal end of CdS nanoribbon (scale bar is 3 μm).

Fig. 3. (a) 3D-simulation of E-field distributions for the sample with guided modes at wavelength of 510 nm. Inset is the E-field distributions profiles along the width direction at the terminal end of the CdS nanoribbon marked with dashed red line. (b) the simulated cross-sectional (x-y plane and y-z plane) E-field distribution in CdS nanoribbon (y-z plane was plot just along the center at one rank of Au nanodisks). (c) The charge distribution of one representative Au nanodisk.

Fig. 4. Correlation between the number of emitted light spots and DC. (a₁), (b₁) and (c₁), the SEM images of the terminal end of the sample containing three rows of Au nanodisk array with DC of about 0.45 μm , 1.5 μm and 2.2 μm , respectively. (a₂), (b₂) and (c₂) are their dark field optical micrographs under the local excitation of 488 nm laser, (all of the scale bars are 3 μm). (a₃), (b₃) and (c₃), the calculated E-field distribution for the cross-section (x-y plane) of corresponding hybrid structures.