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High intensity enhancement of unidirectional propagation of a surface plasmon polariton beam in a metallic slit-groove nanostructure

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Abstract. We propose an innovative design for metallic slit-groove nanostructure to increase the propagation intensity of a unidirectional Surface Plasmon Polariton (SPP) light beam. Our idea is based on the combination of the concept of unidirectional plasmonic wave propagation in a metallic slit-groove nanostructure and the well-known hybrid modes of a hybrid metal-dielectric waveguide. Our results demonstrate that the hybrid structure results in up to 5 times enhancement in the SPP beam intensity relative to the conventional design of slit-groove nanostructure. This new design of SPP based nano source can be applied in many applications including nano photonic devices.

1. Introduction

Excitation of surface plasmon effects at the interface of metal and dielectric establishes the ground for manipulating light in sub-wavelength scales [1-5]. In contrast to photonic waveguides, light confinement in the plasmonic waveguides is not restricted by the diffraction limit [1,4]. However, the propagation loss in the plasmonic waveguides is intrinsically large, and therefore, the intensity of a Surface Plasmon Polariton (SPP) wave is usually weak. Accordingly, the basic challenge in the field is to overcome this problem and to increase the plasmonic wave transmittance along an interface to develop compact plasmonic devices.

According to conventional diffraction theory, when light falls on a sub-wavelength slit, it will diffract in all directions [6-8]. It has been shown that introducing a periodic array of grooves at the exit side of metal-slit structure results in a localised unidirectional SPP propagating beam [9-11]. This directional beaming effect, identified by Ebbesen et al. [6], has been analysed in conventional design of slit-groove nanostructure to increase the intensity of unidirectional beam [12-15].

Hybrid waveguides composed of plasmonic and index-guiding dielectric guides have recently been a subject of highly interest for research [1-5]. In Ref. [1] a hybrid waveguide capable of confining mode on the area scales of $\lambda^2/400$ to $\lambda^2/40$, while travelling over large distances from 40 to 150 μm, has been reported.

In this paper, we integrate a semiconductor nano strip with high index dielectric constant to form a dielectric waveguide above the metal surface at the right hand side of slit-groove structure (see Figure 1). Using COMSOL Multiphysics software a finite element based software; we demonstrate that this design can increase the intensity of unidirectional SPP beaming, greatly.

2. Theoretical background

When light illuminates the aperture of the hybrid structure, depicted in Figure 1, it transmits through

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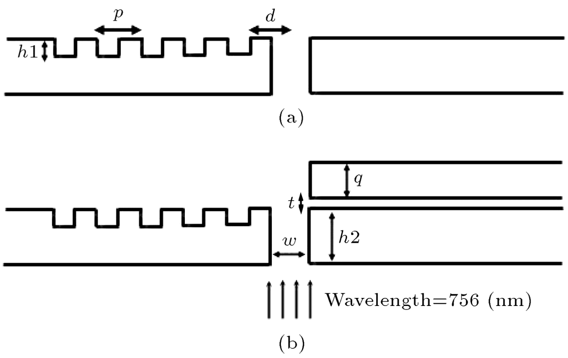

Figure 1. Conventional (a) and hybrid (b) slit-groove nanostructure. Geometrical parameters of the structure are shown in the figure.

the aperture by diffraction in all directions and a part of its energy couples to surface plasmons on the metal-low index dielectric (Ag-SiO_2) interface, on the right hand side. In addition, a portion of its energy couples to surface plasmon waves propagating along the metal grating on the left hand side of the structure [13]. Also, a part of illumination light couples to the dielectric waveguide modes in the semiconductor (GaAs) nano strip above the metal. High index dielectric surrounded by low index SiO_2 also supports dielectric waveguide modes. When these dielectric and plasmonic guides are brought together, a hybrid mode is formed. Propagation properties of this hybrid mode depend on the original SP and dielectric modes. the physics of hybrid plasmonic waveguides has been described in great depth in Ref. [1].

When SPPs propagate through the periodic array of metallic grooves, they diffract in different angles. For a special grating pitch size, the SPP waves, propagating in the grating region, will reflect and interfere constructively. In such conditions, the subsequent grooves form an optical Bragg mirror [11]. This is satisfied by Eq. (1), hence maximizing the reflectance of SPPs by periodic grooves:

$$K_{SP}.P = m\pi, \qquad (1)$$

where K_{SP} is the SP wave vector, P is the grating pitch size and m is an integer. The reflected SPPs will interfere with the original right-going SPP waves in the metal-dielectric interface. If the distance between slit centre and the first groove is expressed by d, the total phase difference, φ, between these two SP waves is expressed as:

$$\varphi = 2K_{SP}.d + m\pi. \qquad (2)$$

Destructive/constructive interference will occur if φ is an odd/even multiple of π. This is controlled by the distance between the first groove and the slit center [12,13]. Thus at a given wavelength, by proper selection of the geometrical parameters, d and p, the intensity of the left-going SPP mode can be minimized so that the intensity of the SPP mode propagating in the right hand side of the nano slit gets its maximum. This provides focusing of the light emerging from the sub wavelength slit in the demanded direction in the form of intense localized unidirectional SPP wave.

Thus there are two SPP-light couplings that are present in the hybrid nanostructure. One from the coupling of the plasmonic waves in the conventional metallic slit-groove nano structure of the two sides of the nanostructure, and the second, the coupling of the high-index dielectric modes of the GaAs waveguide with the ultimate right propagating SPP mode at the silver-SiO_2 interface. These two mode couplings remarkably improve the confinement property and the intensity of the localized unidirectional beam in the hybrid metallic slit-groove nanostructure.

3. Results and discussion

In order to evaluate the performance of our proposed nanostructure, we simulate light transmission through the hybrid nanostructure shown in Figure 1(b) and compare the results with that of conventional design of metallic slit-groove nanostructure (the one without nano strip in Figure 1(a)). To this end, we consider normally back side illumination of slit by a TM-polarized plane wave with wavelength=617 nm. The permittivity of silver is -17.24-$j*0.50$ [16] and its thickness is set to be 300 nm. We consider 5 periodic grooves with filling factor of 0.5 and with grating period of $p = 200$ nm corresponding to the condition that Eq. (1) is satisfied. The slit width is set to 90 nm in all simulations. We apply a Perfect Matched Layer (PML) boundary condition to avoid unwanted reflections. After selection of the pitch size, p, based on simple design rule of Eq. (1), slit-array distance, d, is varied from 200 nm to 1000 nm to find the best value corresponding to constructive interference between the reflected left-going SPP wave and the original right-going one. The mode current density, J, has been evaluated along a cut line on the Ag-SiO_2 interface of the slit-groove nanostructure. Figure 2 shows the variation of J versus the distance d. The total phase difference between the two interfering SPP modes depends only on the parameter d. Thus constructive and destructive interference results in oscillatory dependence of mode current density on the distance, as shown in Figure 2. The distance $d = 300$ nm was chosen for the next results which is the first resonance condition of the slit-groove nanostructure.

To realize the impact of grating depth on the SPP unidirectional beam intensity, we keep all the geometric parameters fixed and varying depth, $h1$, from 60 to 180 nm. We define a cut line on the Ag-SiO_2 interface and evaluate the electric field energy, $E_s = \int E^2 dl$

along this line for the structure without dielectric nano strip. The result has been shown in Figure 3. We obtain the optimum value of E_s for $h1 = 140$ nm, so we set this value for remaining simulations.

Figure 4 shows simulation results for $h1 = 140$ nm

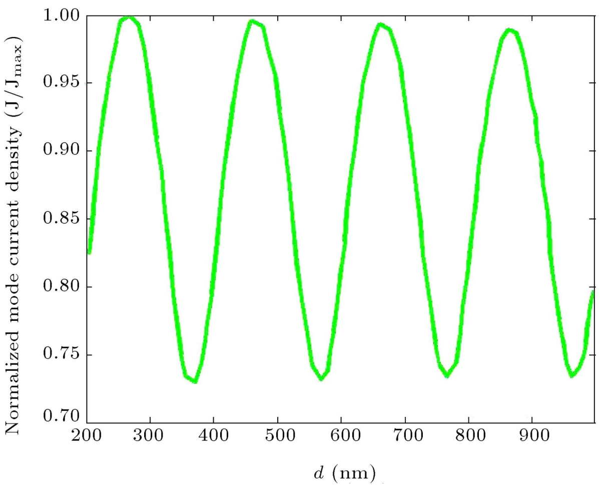

Figure 2. Variation of current density norm versus the distance d.

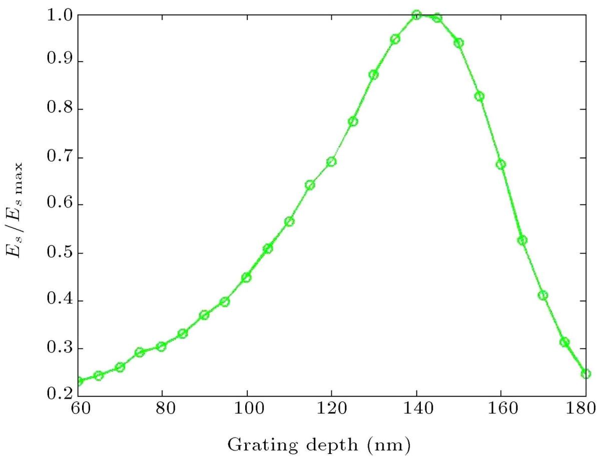

Figure 3. Variation of electric field energy versus grating depth, $h1$.

and $h1 = 80$ nm. As can be seen, amplitude of electric field in the case of $h1 = 140$ nm is much greater than that at $h1 = 80$ nm. We find that the electric field energy at $h1 = 140$ nm is 3 times larger than that at $h1 = 80$ nm. Figure 5 shows the profile of electric field amplitude in the hybrid structure. As shown in this figure, electric field is highly confined in narrowly low index region between metal and the dielectric nano strip. To compare the performance of the standard structure with the hybrid one proposed in this work, we have evaluated the amplitude of electric field along a cut line $t/2$ nm above the metal surface.

As shown in Figure 6, the amplitude of electric field for hybrid structure is significantly stronger than that of standard one. The amplitude of electric field depends on resonance conditions between dielectric and plasmonic mode and therefore is affected by geometrical parameters such as dielectric nanostrip thickness, q, and low index region distance between metal and dielectric, t. For instance, the value of electric field energy along, E_s, at $t = 2$ nm and $q = 340$ nm, is about 5.5 times greater than that for conventional structure,

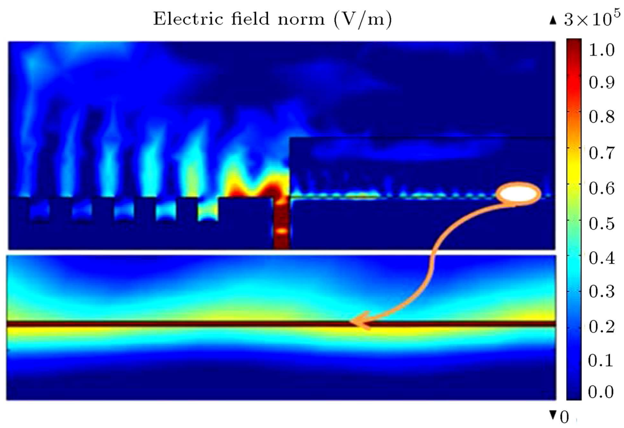

Figure 5. The amplitude of electric field for the composite structure at $t = 2$ nm and $q = 340$ nm. The narrow low index region is shown in an expanded form to be viewed clearly.

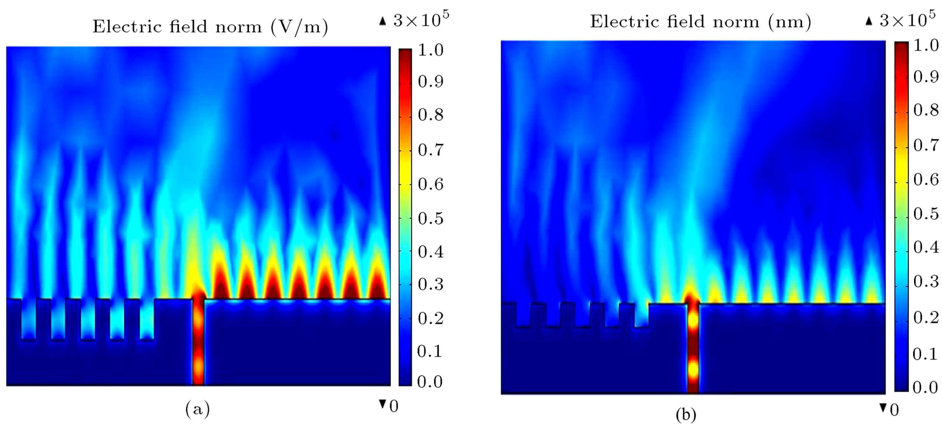

Figure 4. Profile of electric field amplitude versus grating depth, $h1$, of (a) 140, and (b) 80 nm in the standard structure.

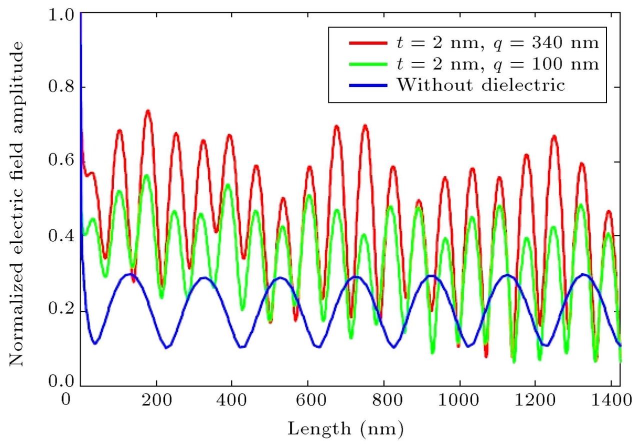

Figure 6. Electric field amplitude along a cut line $t/2$ nm away from metal surface for conventional structure without dielectric nano strip and for the composite one at $t = 2$ nm, $q = 340$ nm and $t = 2$ nm, $q = 100$ nm.

while this ratio is about 3.5 times at $t = 2$ nm and $q = 100$ nm.

4. Conclusions

We have studied transmission of light through a sub wavelength slit on a composite structure consisting of a metallic slit-groove structure and a hybrid plasmonic waveguide. Simulation results show that not only the intensity of unidirectional SPP-beam can be enhanced greatly, but also final light beam is confined to a very thin low index layer. Geometrical parameters of the dielectric waveguide and metallic grating influence improvement conditions. These results can be used for controlling high intensity confined light in plasmonic devices for a wide range of applications in integrated optics, nano lithography, and sensing.

References

1. Oulton, R.F., Sorger, V.J., Genov, D.A., Pile, D.F.P. and Zhang, X. "A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation", *Nat. Photonics*, **2**(8), pp. 496-500 (2008).
2. Alam, M.Z., Meier, J., Aitchison, J.S. and Mojahedi, M. "Super mode propagation in low index medium", *Quantum Electronics and Laser Science Conference*, Baltimore, Maryland United States, pp. JThD112 (2007).
3. Huang, Q., Bao, F. and He, S. "Nonlocal effects in a hybrid plasmonic waveguide for nanoscale confinement", *Opt. Express*, **21**(2), pp. 1430-1439 (2013).
4. Alam, M.Z., Meier, J., Aitchison, J.S. and Mojahedi, M. "Propagation characteristics of hybrid modes supported by metal-low-high index waveguides and bends", *Opt. Express*, **18**(12), pp. 12971-12979 (2010).
5. Chen, L., Zhang, T., Li, X. and Huang, W. "Novel hybrid plasmonic waveguide consisting of two identical dielectric nanowires symmetrically placed on each side of a thin metal film", *Opt. Express*, **20**(18), pp. 20535-20544 (2012).
6. Ebbesen, T.W., Lezec, H.J., Ghaemi, H.F., Thio, T. and Wolff, P.A. "Extraordinary optical transmission through sub-wavelength hole arrays", Nature, 391(6668), pp. 667-669 (1998).
7. Martín-Moreno, L., García-Vidal, L.F., Lezec, H.J., Degiron, A. and Ebbesen, T. "Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations", *Phys. Rev. Lett.*, **90**(16), p. 167401 (2003).
8. Lin, D.Z., Cheng, T.D., Chang, C.K., Yeh, J.T., Liu, J.M., Yeh, C.S. and Lee, C.K. "Directional light beaming control by a subwavelength asymmetric surface structure", *Opt. Express*, **15**(5), pp. 2585-2591 (2007).
9. Kim, H. and Lee, B. "Unidirectional surface plasmon polariton excitation on single slit with oblique backside illumination", *Plasmonics*, **4**(2), pp. 153-159 (2009).
10. Lee, Y., Hoshino, K., Alú, A. and Zhang, X. "Tunable directive radiation of surface-plasmon diffraction gratings", *Opt. Express*, **21**(3), pp. 2748-2756 (2013).
11. Lezec, H.J., Degiron, A., Devaux, E., Linke, R.A., Martin-Moreno, L., Garcia-Vidal, F.J. and Ebbesen, T.W. "Beaming light from a subwavelength aperture", *Science*, **297**(5582), pp. 820-822 (2002).
12. Chen, P., Gan, Q., Bartoli, F.J. and Zhu, L. "Near-field-resonance-enhanced plasmonic light beaming", *IEEE Photonics J.*, **2**(1), pp. 8-17 (2010).
13. López-Tejeira, F., Rodrigo, S.G., Martín-Moreno, L., García-Vidal, F., Devaux, J.E., Ebbesen, T.W., Krenn, J.R., Radko, I.P., Bozhevolnyi, S.I. and González, M.U. "Efficient unidirectional nanoslit couplers for surface plasmons", *Nat. Phys.*, **3**(5), pp. 324-328 (2007).
14. González, M., Weeber, J.C., Baudrion, A.L., Dereux, A., Stepanov, A., Krenn, J., Devaux, E. and Ebbesen, T. "Design, near-field characterization, and modeling of 45° surface-plasmon Bragg mirrors", *Phys. Rev. B*, **73**(15), p. 155416 (2006).
15. Randhawa, S., González, M.U., Renger, J., Enoch, S. and Quidant, R. "Design and properties of dielectric surface plasmon Bragg mirrors", *Opt. Express*, **18**(14), pp. 14496-14510 (2010).
16. Johnson, P.B. and Christy, R.W. "Optical constants of the noble metals", *Physical Review B*, **6**(12), pp. 4370-4379 (1972).

Biographies

Behrooz Eftekharinia received his MSc degree in the field of atomic physics, in 2012, from Amirkabir

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Seyed Hassan Nabavi received his MSc degree in the field of atomic physics in 2001 from Tehran University. His master thesis is mainly devoted to laser spectroscopy. He joined Physics Department of Tarbiat Modares University as the first PhD student of the new established nanooptics lab in 2010. His PhD research is on application of plasmonic materials for improvement of performance of a laser.

Ahmad Moshaii, Associate Professor, received his PhD degree from Physics Department of Sharif University of Technology in 2004 in the field of sonoluminescence. Then he worked at IPM as a Postdoc researcher with concentration on RPC detectors. Dr. Moshaii joined Tarbiat Modares University (TMU) in 2008 and established a nanooptics lab in Physics Department. Currently, his research interest concentrates on plasmonic materials for solar harvesting systems including solar cells and photoelectrochemical water splitting cells.

Ali Dabirian received his PhD, in photonics, in 2010, from Ecole Polytechnique Federale de Lausanne (EPFL) in Lausanne, Switzerland. He conducted research on water splitting, in Delft University of Technology, in Delft, Netherlands, as a postdoctoral researcher, after which he joined Sharif University of Technology in Iran as an Assistant Professor of physics. Currently, he is a researcher in Photovoltaics and Thin Film Electronics Laboratory of EPFL in Neuchatel, Switzerland. His research interest lies in optical materials for solar fuels and photovoltaics.