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.

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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. [9], 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 \(\mu\)m, 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
the aperture by diffraction in all directions and a part of its energy couples to surface plasmons on the metal-
low index dielectric (Ag-SiO₂) 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 die-
electric waveguide modes in the semiconductor (GaAs)
nano strip above the metal. High index dielectric
surrounded by low index SiO₂ 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 SPs propagate through the periodic array of
dielectric grooves, they diffract in different angles. For
a special grating pitch size, the SPP waves, propagating
in the grating region, will reflect and interfere con-
structively. 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:

\[ K_{SP} P = m \pi, \]

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, \( \varphi \), between these two SP waves is
expressed as:

\[ \varphi = 2K_{SP} d + m \pi. \]

Destructive/constructive interference will occur if \( \varphi \)
is an odd/even multiple of \( \pi \). 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-SiO₂ 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 \( -17.24-j \times 0.50 \) [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 cor-
responding 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
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-SiO₂ 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, \( h_1 \), from 60 to
180 nm. We define a cut line on the Ag-SiO₂ interface
and evaluate the electric field energy, \( E \), along
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 $h_1 = 140$ nm, so we set this value for remaining simulations.

Figure 4 shows simulation results for $h_1 = 140$ nm and $h_1 = 80$ nm. As can be seen, amplitude of electric field in the case of $h_1 = 140$ nm is much greater than that at $h_1 = 80$ nm. We find that the electric field energy at $h_1 = 140$ nm is 3 times larger than that at $h_1 = 80$ 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.
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


Biographies

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**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.