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Ring grating-nanoprism structure for efficient focusing of surface plasmon polaritons

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ABSTRACT

This work aims to study light-matter interaction at the nanoscale by integrating emitters with plasmonic structures. Our proposed structure consists of metallic nanoprisms in the center of ring diffraction gratings. Surface plasmon polaritons (SPPs) are generated by the ring grating which propagate and get focused on the nanoprism tip forming an intense electromagnetic hotspot in the region. FDTD numerical simulations are done to calculate the optimized angle of incidence needed for SPP excitation by the ring grating. Sample fabrication and optical characterization methods are presented to study the coupling between generated SPPs and CdSe quantum dots placed in the center. FDTD simulations as well as experimental observations are done to study the electromagnetic hotspot at the tip of the ring grating-nanoprism structure. This work will be extended further to include the coupling between SPPs and emitters placed in the hotspot which leads to their photoluminescence and lifetime enhancement.

Keywords: ring grating, nanoprism, surface plasmon polaritons, field enhancement, fluorescence lifetime.

1. INTRODUCTION

Controlling and enhancing surface plasmon launching, propagation, and localization has been one of the key goals in the fields of plasmonics, nanooptics and nanophotonics [1]. In addition, metallic nanoparticles and nanoantennas have been intensively studied due to their capability to increase electromagnetic field confinement [2] leading to a remarkable enhancement of the fluorescence rate and quantum yield of emitters placed in their vicinity [3-5]. However, the diffraction of light limits the optical resolution as well as the localization of electromagnetic fields in confined volumes, which is essential in numerous applications ranging from optical electronics to nanofabrication and sensing devices. A useful approach for solving this problem involves coupling between propagating SPPs and localized surface plasmons (LSPs) which showed to be very efficient in subwavelength confinement. C-aperture ridge waveguides, i.e. C-shaped subwavelength holes in metallic films, showed big potential in achieving high resolution as well as transmission enhancement [6, 7]. When excited resonantly, plasmonic ring gratings cause a highly focused electromagnetic field located in its center [8]. Combining ring diffraction gratings with nanoscale apertures and nanoantennas also causes SPP-LSP coupling leading to a highly localized and enhanced electromagnetic field at the nanoantennas [9-11].

In this work, we study a plasmonic structure consisting of a metallic nanoprism placed in the center of a ring diffraction grating. The ring grating is responsible of generating SPPs that propagate along the ring diameter and couple with LSPs present at the nanoprism tip. Placing emitters in the hotspot leads to an increase in their photoluminescence decay rate as well as an increase in their lifetime.

2. METHODOLOGY

When illuminated resonantly, a plasmonic ring grating generates SPPs that propagate along the ring diameter and get focused in the center. The SPP wavevector k_{SPP} follows the conservation of momentum relation:

$$k_{SPP} = n_0 k_0 \sin \theta_0 + \frac{2\pi}{d} \quad (1)$$

where n_0 and k_0 are the free space index of refraction and wave vector, θ_0 is the illumination angle relative to the surface normal, and d is the grating period. Because of the concentric focusing property of the ring grating, we propose placing a nanoprism in the center where the electromagnetic energy reaches its maximum. When the SPPs reach the nanoprism, they are guided along the sides and get focused at the tip where they form an electromagnetic hotspot.

In the following section, we present experimental and numerical simulation results that were done to study the ring grating structure as well as the ring grating-nanoprism structure.

3. RESULTS

Ring grating

We fabricated ring gratings with diameters varying from 50 μm to 300 μm on glass and Si substrates, as seen in Figure 1. Due to the conservation of momentum (Eq. 1), their periods can be chosen according to the incident light wavelength. The ring gratings shown in Figure 1 have a period of 800 nm which allows them to get excited by a 980 nm laser. Electron Beam Lithography (EBL) was used to fabricate the ring gratings where a 200 nm layer of PMMA is deposited by spin coating (4000 rpm) on the substrate. Then, the EBL process is carried out and is followed by the evaporation of a 3 nm Chromium adhesion layer and a 150 nm gold layer. No lift off is done to maintain the gold layer between the grooves which is necessary for the SPP propagation. The SEM images in Figure 2 show a ring grating with a 100 μm diameter and 800 nm period. The slight error in the grating period dimensions is due to the electron beam dose used in fabrication.

Figure 1: Optical image of gold ring gratings of 50 μm , 100 μm , 200 μm and 300 μm diameters on a glass substrate.

Figure 2: SEM images of a ring grating of 100 μm diameter and 800 nm period.

In order to test the ring gratings and the SPP propagation, we use an optical fiber to illuminate the ring grating at a certain position. This leads to the excitation of SPPs that are observed to propagate along the ring diameter and couple out again upon reaching the other side of the ring (Figure 3-a). The optical image in Figure 3-b shows a 100 μm ring grating with 800 nm period on Si substrate excited by a 980 nm laser source. The generated SPPs couple out into the far-field after propagating along the ring diameter and a transmitted spot is observed. This allows us to verify that the SPPs are propagating with a specific wavevector k_{SPP} perpendicular to the grating grooves.

Figure 3: a) Schematic of the fiber coupling setup b) Optical image of a 100 μm ring grating with 800 nm period showing the SPP propagation.

FDTD simulations were done using Lumerical software to calculate the optimized angle of incidence that should be used to excite the ring gratings. An incident linearly polarized light of 980nm wavelength is used to illuminate a grating with 800 nm period on a Si substrate, and the resulting propagating electric field is obtained at a distance away from the grating. The results show that the incident light has to be at a positive angle of 6 degrees or a negative angle of -11 degrees for maximum coupling efficiency (Figure 4). This agrees with the results obtained in the literature [12].

Figure 4: Electric field transmission as a function of the angle of incidence.

In order to study plasmon-emitter coupling, CdSe quantum dots are placed in the center of a 50 μm ring by using minirobots with micrometer metal tips and are then excited with a 405nm pulsed laser. The lifetime of these quantum dots is measured on glass and gold substrates as well as inside the rings using a time-correlated single photon counting setup. The obtained ratio of their lifetime on glass to that on gold is 1.5. FDTD simulations of the emitters' spontaneous decay rate are also performed and result in a similar glass to gold ratio equal to 1.8 (Figure 5). As for the lifetime of emitters inside the rings, we do not observe any difference compared to those on gold. This is because the rings are too big in size to observe any enhancement. In order to start observing some fluorescence enhancement, we should move to a much smaller scale and integrate nanoantennas inside the ring.

Figure 5: a) CdSe quantum dots placed inside the ring grating b) Experimental CdSe lifetime on glass, gold and inside grating c) FDTD simulations of the spontaneous decay rate on glass, gold, and inside grating.

Ring grating / nanoprism

In this section, we describe our proposed structure made of nanoprisms integrated in the center of the ring structures. First, we performed FDTD simulations using Lumerical software where a linear TM polarized plane wave (perpendicular to the grating grooves) is incident on a grating with period $d = 525 \text{ nm}$. The wavelength of the incident light ranges from 500 nm to 1000 nm and is incident at an angle of -11° for maximum coupling efficiency (based on the results of Figure 4). A nanoprism with 250 nm side length and 100 nm thickness is placed 2.5 μm away from the grating with one of its sides parallel to the grating grooves. The dimensions of the nanoprism are kept in the nanometer range due to extremely long simulation times. A monitor is placed on the surface of the grating and nanoprism, i.e. at a height of 100 nm, to record the electric field at different positions. Illuminating the grating with an incident plane wave generates SPPs that propagate perpendicular to the grating grooves towards the facing nanoprism side. Upon reaching the nanoprism, SPPs are directed along the two other sides and get focused at the tip where they form an intense electromagnetic hotspot. As can be seen from Figure 6-a, the electromagnetic field recorded by a video monitor at the surface of the structures forms a hotspot at the nanoprism tip. For a quantitative analysis, we measure the electric field intensity E_z (perpendicular to the substrate) along the x -direction and for a given y at the position of the nanoprism tip. The results are shown in Figure 6-b where the electric field intensity forms a peak at the nanoprism tip due to the hotspot formed in that region.

Figure 6: a) Simulation of the electric field intensity for a nanoprism facing a grating showing hotspot at the tip b) Electric field intensity E_z (perpendicular to the substrate) along the x -direction for y at the position of the nanoprism tip.

With this motivation in mind, we succeeded in fabricating the proposed structure made of a nanoprism in the center of a ring grating. The fabrication was done by EBL on Silicon substrates followed by the evaporation of a 3 nm Chromium layer and a 120 nm layer of gold. In Figure 7, we show an SEM image of a ring grating of 20 μm diameter and 525 nm period. The nanoprism fabricated in the center has a 2 μm side length.

Figure 7: SEM image of a ring grating of 20 μm diameter and 525 nm period with a nanoprism of 2 μm side length in the center.

In order to test our structures, we place our sample under a home-built confocal microscope system of high sensitivity. This setup includes a Peltier-cooled CCD camera and a 50X, NA= 0.95 microscope objective. A 633 nm laser is made incident on the ring grating at a specific position facing the nanoprism side, as shown in the optical image of Figure 8. The bright incident laser spot has a very high intensity that saturates the CCD camera and could not be filtered out entirely. The 633 nm laser source is compatible for exciting the grating with $d=525$ nm, which generates SPPs causing a bright spot to appear exactly at the position of the nanoprism tip as expected from simulations.

Figure 8: Optical image of a hot spot created at the tip of a nanoprism of 2 μm side length placed in the center of a ring grating of 20 μm diameter. The high intensity of the incident laser spot saturates the CCD camera and could not be filtered out.

4. CONCLUSION

In this work, we show that a plasmonic ring grating can be successfully used to launch and direct SPPs and to study plasmon-emitter coupling at the nanoscale. FDTD numerical simulations and experimental observations are presented to characterize the structure. We also demonstrate how our proposed ring grating-nanoprism structure makes use of the high energy of propagating SPPs and the sub-wavelength confinement of LSPs to achieve efficient optical nano-focusing at the nanoscale. This is clarified by the observation of an electromagnetic hot spot at the tip of the nanoprism.

The next step in this work would be to spread emitters on the surface and to observe their fluorescence and lifetime enhancement caused by the created hot spot. Fabricating single and double bowtie nanoantennas in the center of the ring is also expected to increase the electromagnetic confinement in their gap. This can be applied at a smaller scale aiming to reach the strong coupling regime between emitters and our integrated ring grating-nanoantenna system

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