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Au-nanoparticles strip-loaded channel waveguide

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Abstract. A strip-loaded channel waveguide was fabricated by deposition of Au nanoparticles (AuNPs) in a thin strip via organometallic chemical vapor deposition on top of a polystyrene slab waveguide. The beam confinement is demonstrated experimentally, despite the absence of a classical closed layer for strip-loading. The AuNP density conditions for plasmonic waveguide hybrid transmission devices are discussed, typically applied in plasmonic sensing.

Keywords: channel waveguide, Au nanoparticles, strip loading, plasmonic sensing, transmission.

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1 Introduction

Plasmonic nanoparticles exhibit localized surface plasmon resonance (LSPR) whose frequency is dependent on the local refractive index.[1] This dependency renders them valuable in sensing applications. Plasmonic-waveguide hybrid sensors[2-4] are a type of LSPR sensors known for their robust and compact structures, flexible polarizations, and high signal to noise ratios. We have recently demonstrated a high-sensitivity sensor in a simple slab waveguide transmission experiment with excellent signal and signal-to-noise-ratio[3], despite the waveguide mode, with a wavelength very close to the LSPR, traveling through a 1.6-cm circular spot of AuNPs with a density of 2.7×10^3 particles/μm^2. Multiplexing, with n analytes in parallel, is not economic with such spot arrangement, due to the large size requirement and inefficient use of gold. A channel waveguide approach with n parallel channels carrying the AuNPs is an economic alternative. However, the production of channel waveguides usually takes significant efforts, thus limiting its commercialization potential. We therefore decided to implement the strip-loading approach for channel definition[5] by applying AuNPs as the strip material as a first step towards a multiplexing approach. It is necessary to first demonstrate that a non-closed strip-loading material, such as the randomly positioned AuNPs, are able to serve and allows beam confinement and guidance.

2 Materials and Methods

AuNPs were deposited as previously described with modifications.[3] A thin line (< 0.5 mm) was carved out of a piece of silicon sheet (Grace Bio-Labs, 0.5 mm thick) that is the same size as the slab waveguide (2.5 cm x 5 cm, fused silica substrate with coupling grating and polystyrene waveguide spin coated on top) with two scalpel blades (X- Acto, no. 2) pressed together. The sheet was then gently placed on top of the slab waveguide. The waveguide/silicon sandwich was exposed to UV activated ozone for 2 min after adding 1 mL of H_2O_2 into the ozone chamber. AuNPs were deposited via organometallic chemical vapor deposition (OMCVD) at 65°C for 7 min. The grown AuNPs formed a purple line at the area exposed by the silicon sheet (Fig.1A), which is referred to as the gold channel in this letter. Due to their purplish color, the absorption of the AuNPs lies in the red spectral region, far from the green HeNe laser used here. The gold channel (dark grey line in Fig.1A and black line in the scheme of Fig. 1B) extends from the inside of the coupling grating (semicircle in Fig.1B) to the end of the waveguide, purposely deviating from the normal to the grating edge by ~1° (called horizontal angle; Fig.1B: angle between grey dashed line and black line). A more detailed scheme of the coupling zone is depicted in Fig.2. According to scanning electron microscopy measurements (not shown), the average density of AuNPs is 1.7×10^3 particles/μm^2.

A green HeNe laser (Research Electro-Optics Inc., λ = 543 nm, 0.5 mW) was launched into the polystyrene slab waveguide via the coupling grating at a fixed vertical coupling angle on a spot in close proximity to where the gold channel intersects the grating edge (black spot in Fig. 1B). The coupling spot was then moved on the grating edge along the direction indicated by the arrow in Fig. 1B, resulting in a series of propagating mode patterns (Fig. 3A-E).

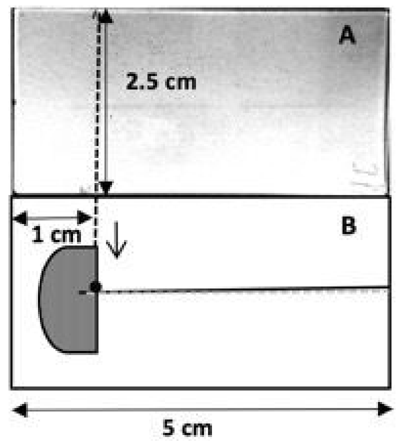

Fig.1 (A) Photograph of the slab waveguide with a gold channel in the middle, weakly visible as a dark grey line. The dashed line marks the edge of the coupling grating. The grey scale and the contrast was adjusted for maximal visibility of the channel. (B) Illustration of the waveguide features: the coupling grating (semicircle), the normal to the grating edge (dashed grey line), and the gold channel (solid black line).

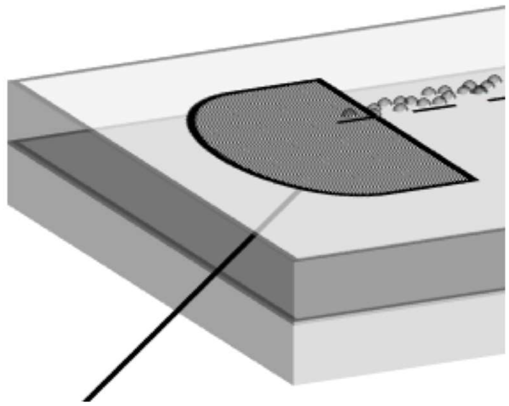

Fig.2 Scheme of the waveguide geometry close to the coupling grating (not to scale): the solid line represents the incoming laser beam; the dark grey half circle is the coupling grating area; the dotted line represents the normal to the coupling grating lines and the nanoparticles are located in a stripe under an angle to the grating normal.

3 Results and Discussion

At the starting position outside the gold channel (black dot in Fig. 1), the laser beam is launched exclusively into a slab waveguide mode (Fig. 3A), propagating parallel to the grating normal and through the entire field of view. However, the gold channel in close proximity touches the slab mode on the bottom side increasingly further down the propagation direction, which leads to a slanted edge at the bottom while keeping the straight edge at the top. The region where the gold channel is located appears black in Fig. 3A. Moving the laser into the gold channel (Fig. 3B) leads to a major coupling into the gold channel waveguide mode propagating under the 1° angle upward in a confined fashion for more than 2 cm, and a minor coupling into a slab waveguide mode propagating straight. Gradually moving the coupling position along the direction indicated by the arrow in Fig. 3B shifts the distribution of the coupled photons between the two modes towards the slab waveguide mode (Fig. 3C-E) which propagates further in comparison to the gold channel waveguide mode. As further down the coupling spot is located, less and less photons are launched into the gold channel waveguide, but more and more into the slab waveguide mode. Fig. 3B-D show the two streaks, in Fig. 3E only the slab waveguide mode is left showing one streak.

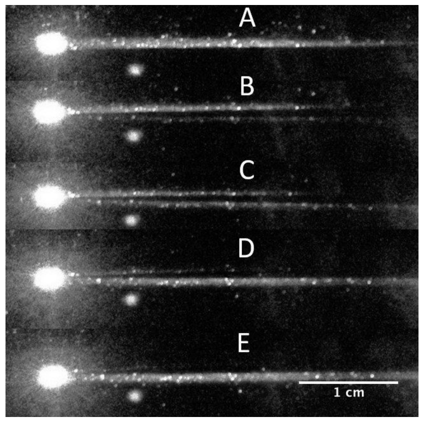

Fig.2 (A-E) Propagating mode profiles obtained by taking snapshots of the propagation streaks as the coupling spot was moved from the starting position (black dot in Fig. 1B) toward the other side of where the gold channel intersects the grating edge. The vertical incident angle was kept constant throughout the experiment.

If the laser is not close to the AuNP only the slab mode is excited; in the case when the laser is only located on the AuNP then the strip-loaded channel waveguide mode is exited solemnly. When the laser is launched partially on the AuNP line and partially on the slab waveguide both modes are exited independently from each other. The amount of photons launched into each mode depends on the precise position of the laser. There is no coupling between the slab waveguide mode and the strip-loaded mode when they are still close together (Fig.3A).

Coupling at a fixed vertical coupling angle and under two different horizontal angles (0° and 1°) into two different modes, one classical slab waveguide mode and one strip-loaded channel waveguide mode, is possible as the effective refractive indices of the slab waveguide mode propagating straight and the strip-loaded waveguide mode with the AuNPs on top are not very different under the chosen off-LSPR condition. The strip loaded waveguide should have a higher effective refractive index and would therefore need a higher vertical coupling angle for optimal coupling.[5] Also the coupling under a horizontal angle of 1° demands a slightly higher vertical coupling angle.[6] However, both effects seem so small even in combination that both modes can be launched within the alignment accuracy and the laser beam's natural divergence offering a small coupling angle spectrum at the grating edge. Probably both modes are not coupled with the highest possible coupling efficiencies. Nevertheless, strip loading with a non-closed strip layer of AuNPs shows beam confinement. .

Because AuNPs absorb visible light very strongly, especially close to the LSPR where the plasmonic-waveguide hybrid sensors are operated, it is essential that their density is below a certain threshold for the gold channel to be functional in a transmission device. On the other hand, the density needs to be high enough to define the channel by strip-loading and offer enough AuNP for the sensing interaction. This trade-off is known in devices which are based on transmission and absorption features. In this experiment, the amount of absorption is minimized - for testing the idea of AuNP strip-loading - by utilizing a laser with a wavelength far from the LSPR wavelength of the AuNPs. The propagation length off-LSPR in the gold channel waveguide, visible in the streak (Fig.3B and C) by a simple photograph, taken without any light amplification, lies in the order of 2.5 cm. In the previously demonstrated transmission sensor[3] which operated very close but not on the LSPR, an average density of 2.7×10^3 particles/μm^2 (> 1.7×10^3 particles/μm^2 used here) along 1.6 cm propagation length has led to successful transmission and sensing. It seems therefore reasonable that a AuNP density in the order of $1\text{-}3\times10^3$ particles/μm^2 can be used for strip-loaded channel waveguides with an active sensing length between 1-2 cm. The effective refractive index of the AuNP strip-loaded waveguides, and therefore the channel beam confinement, will even increase when coming closer to the LSPR due to the anomalous dispersion of AuNPs[7] increasing the strip's refractive index and therefore the effective refractive index of the propagating channel waveguide mode.

This strip loading approach for channel waveguide fabrication is probably applicable only for relative wide channel waveguides, as demonstrated here with the example at 0.5 mm. For high integration devices with channel waveguide width in the order of µm this technology might fail. However, in a multiplexing sensing system when a cuvette system with n individual cuvette channels needs to be adapted to the devices, very high integration is not absolutely necessary so that these coarse channel waveguides are an excellent choice, also providing a substantial surface area for the recognition reactions.

4 Conclusion

The approach of a non-closed layer of AuNPs for strip-loading a plasmonic channel waveguide is demonstrated in this letter. This new approach can streamline the mass production of plasmonic-waveguide hybrid sensors and allow the full exploitation of their biosensing potentials.

Acknowledgment

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