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Near-field electrospinning of dielectric-loaded surface plasmon polariton waveguides

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References and links

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1. Introduction

The increasing demand of faster and smaller devices have significantly increased the attention of the scientific world on surface plasmons, since they are now well known to be a way to reduce the dimension of the photonics integrated circuits and, at the same time, to keep high performances in terms of speed and bandwidth [1]. Surface plasmons are surface electromagnetic modes, propagating along metal-dielectric interfaces [2] and are bound to the surface due to the exponential decay of the intensity along the normal direction. Many efforts have been made to achieve efficient lateral confinement in order to efficiently guide surface plasmons. Various waveguiding structures for surface plasmons, fabricated with different techniques, such as metal stripes [3–5] and v-grooves [6,7] have already been investigated. The strong lateral confinement can be also achieved by depositing polymer stripes on a metal surface and using them as waveguides [8–11]. Near field investigation of such dielectric-loaded SPP waveguides (DLSPPWs) has demonstrated that they allow single mode propagation along with long propagation length [12,13]. Linear dielectric nanostructures can also be fabricated by other techniques like e.g. near-field electrospinning (NFES), which has proven to be useful for writing linear nanostructures in well controlled patterns [14,15]. In this paper we will show that NFES can be used to deposit polymer waveguides on a thin gold film. The electrospun polymer nanofibers were initially investigated with an atomic force microscope, in order to evaluate the dimension and therefore calculate the mode effective index, which would give the experimental conditions for the SPP excitation. Subsequent characterization using a scanning near-field optical microscope (SNOM) was used to demonstrate that SPPs can indeed be guided using electrospun nanofibers deposited on a gold film. The advantage of this new fabrication technique, compared to e-beam or ion beam milling, which represent the most widely used so far for v-grooves and polymer ridges respectively, is the simplicity and fabrication speed of NFES. In addition DLSPPW deposition by electrospinning is well suited for rapid prototyping when testing e.g. new plasmonic circuit designs.

2. Materials and methods

2.1 Sample preparation

The sample consists of polymer fibers electrospun onto a thin gold film deposited on an optically flat glass substrate. The polymer solution was made by dissolving 4.0% weight of Poly(ethylene oxide) (PEO) polymer with a molecular weight of 900000 g/mol in a 3:1 mixture of H_2O and tert-butanol. After constant stirring at 250 rpm and 50 ^{0}C for 24 hours the polymer solution was completely dissolved and ready to be spun. The gold coated substrate, onto which the electrospun fibers were to be deposited, was a 10mm x 10mm x 0.5mm fused silica glass substrate coated with 3 nm of chrome and 45 nm of gold by electron beam sputtering. The quality of the gold film was tested by reflecting a collimated laser beam of the glass-gold interface. A large narrow dip was observed in the reflected signal at the excitation angle, which is indicative of a strong surface plasmon resonance, which in turn implies a good quality of the gold film.

2.2 Near-field electrospinning of PEO nanofibers

The PEO solution was electrospun using a homebuilt NFES setup (Fig. 1). A 0.9mm x 50mm (20G x 2") hypodermic needle was used as tip and the tip-to-collector distance and spinning voltage was set to 500 μm and 1000 V respectively. Before electrospinning a small droplet of the PEO solution was deposited at the tip, which was positioned 500 μm away from the intended scan area. Spinning was initiated by poking the droplet with a sharp tungsten tip as demonstrated by Chang *et al.* [15]. After initiating the spinning the collector was moved at a speed of 200 mm/s in a raster scan pattern. The electrospun fibers were deposited in straight parallel 7.5 mm long lines with 150 μm between lines and covering a total area of 4.5 mm x 7.5 mm. The writing of the entire pattern of electrospun fibers took less than 30 seconds after

spinning was initiated. The deposited PEO fibers were left to dry and subsequently characterized by SNOM, atomic force microscopy (AFM) and scanning electron microscopy (SEM).
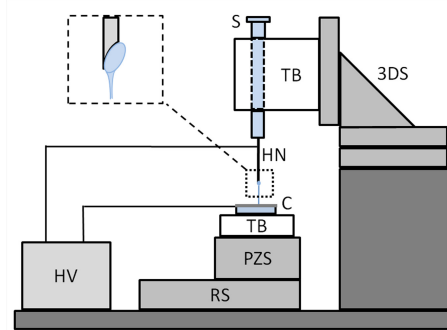

Fig. 1. Schematic of the setup used for near-field electrospinning of DLSPPWs. HV: High voltage supply, HN: Hypodermic needle, RS: Rotation stage, PZS: 2D Piezo stage, 3DS: 3D manual positioning stage, C: Collector, TB: Teflon block, S: Syringe.

The positive output of the high voltage supply (model MJ30P400 from Glassman High Voltage Inc.) was connected to the 20 Gauge hypodermic needle (HN) used as spinneret, while the ground terminal was connected to the gold coated side of the sample substrate, which served as the collector electrode (C). The sample was mounted on top of an XY piezo stage (PZS, model PIHera P-629.2 from Physik Instrumente). An insulating Teflon block (TB) was placed between the sample and the piezo stage to protect the stage. The piezo stage was mounted on the edge of a rotation stage (RS) to allow the stage to be rotated away from the spinneret for easy access to the stage when exchanging samples. The hypodermic needle used as tip was mounted on a 1.0 ml syringe (s). The syringe was fixed onto a Teflon block (TB) that was mounted onto ax XYZ translation stage (3DS) used for rough positioning of the tip relative to the collector (i.e. the sample). As demonstrated by Chang *et.al* [15], NFES can be optimized to produce nanofibers with diameters that vary less than 10% from the average fiber diameter.

2.3 SNOM setup

The investigation of the fibers has been conducted with the SNOM (see Fig. 2). The SNOM was operated in collection mode, which allowed the simultaneous collection of both morphological information and a near-field optical signal from the scanned area.
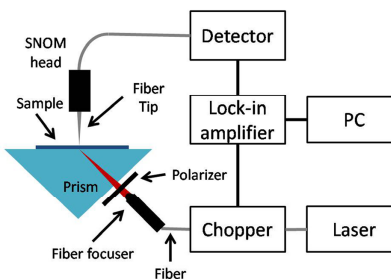

Fig. 2. Schematic of the SNOM setup used for near-field investigation. A detailed description of the setup can be found in [11].

The sample was mounted on a BK7 glass prism with an index matching immersion oil. Surface plasmons were excited through the prism using a Kretschmann-Raether configuration [2]. A lensed fiber was used to focus a p-polarized beam, generated by an infrared tunable laser, which could emit in the wavelength range of 1500-1650 nm. The lensed fiber was

mounted on a rotational stage, used to change the angle of incidence of the excitation beam. An etched uncoated fiber tip was used to raster scan the investigated area, recording the near-field signal and morphological information at the same time. The optical signal was recorded with lock-in detection to improve the signal to noise ratio of the recorded images. A more detailed description of the SNOM setup has been published elsewhere [12].

3. Results and discussion

3.1 Fiber characterization

The AFM and SEM investigation (Fig. 3) reveals that the waveguides are about 1.8 μm wide and 160 nm high. Although these dimensions are not ideal for SPP waveguiding [16], they still allow for guided SPP modes to propagate as demonstrated below. Considering the measured dimensions, the mode effective index of the waveguide is expected to be close to $N_{eff} = 1.15$ [16], and given the dimensions of the electrospun fibers, the expected SPP propagation length was approximately 40 μm [16].
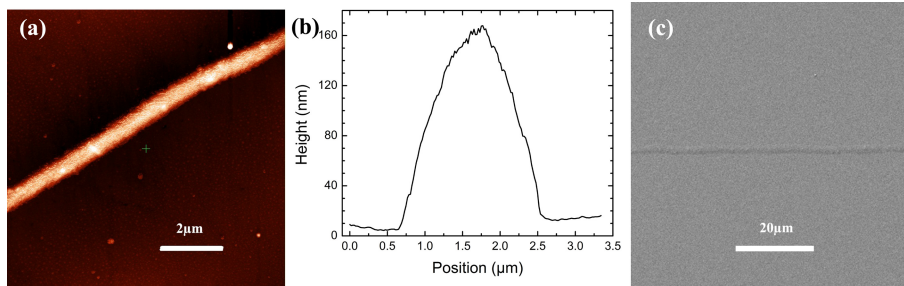

Fig. 3. AFM image of a typical area of the electrospun nanofibers (a), including a cross sectional profile of the fiber that shows the dimensions of the waveguides to be 1.8 μm in width and 160 nm in height (b), SEM image of a nanofiber (c).

3.2 SPP excitation

The excitation beam was focused on the Au film directly below the waveguide using two different angles to excite two different mode effective indexes. After some considerations of the waveguide dimensions illustrated in the previous section, the mode effective index of the fiber is expected to be close to $N_{eff} = 1.15$ [16]. The excited mode effective index can be extracted from the angle of incidence θ_i of the laser on the sample surface, when excitation of DLSPPWs mode is observed with the SNOM. Using the values from Fig. 4(b) and Fig. 4(c), the mode effective index is found to be $N_{eff}(46°) = 1.08$ and $N_{eff}(49°) = 1.14$ respectively. Figure 4 shows how a mismatch of the excited mode effective index results in the disappearance of the mode propagating in the fiber (Fig. 4(b)), which not only proves that surface plasmon are excited inside the waveguide, but also confirms the mode effective index of the fiber. In Fig. 4(d), an averaged cross section taken from the optical signal in Fig. 4(c) shows the good confinement in the waveguide. The full width at half maximum is measured to be approximately 2 μm. The propagation length of the surface plasmon was evaluated from Fig. 4(c) to be $L_p = 10$ μm by measuring the distance from the edge of the excitation spot to the point where the signal had decayed to 1/e times the initial value.
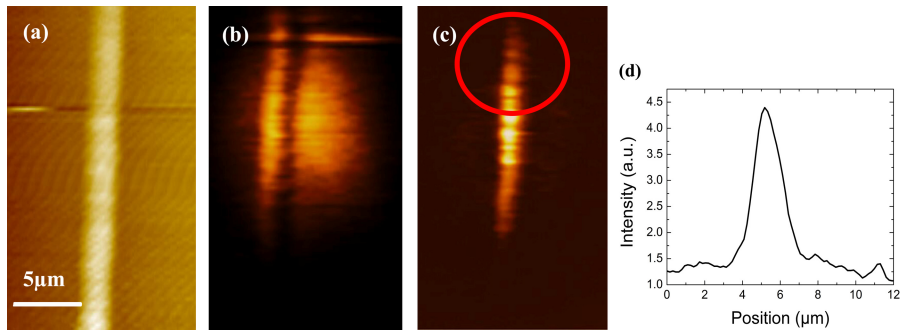
Fig. 4. Near field images demonstrating the excitation of DLSPPW modes in the electrospun fibers. (a) Topography, (b) optical signal at $\theta_i = 46°$, (c) optical signal at $\theta_i = 49°$. When the beam is incident on the sample with an angle that does not match the right effective index no plasmon propagation is detected (b). When the stage is rotated to match the right values of the angle of incidence, the recorded image shows the plasmon propagating in the waveguide, with the excitation beam no longer visible. A red circle marks the area where the excitation beam is focused. An averaged cross section (d) shows the confinement of the plasmon in the waveguide.

3.3 SPP guiding

SPPs were excited inside the waveguide using three different excitation wavelengths (Fig. 5). The laser was focused onto the glass/gold interface of the sample at an angle of incidence of 49°, exciting the mode effective index of $N_{eff} = 1.14$. The SPP near-field signal builds up and propagates in the waveguide and decays rapidly due to the short propagation length given by the geometry of the waveguide and the thickness of the Au film. It is evident that the fiber supports single mode propagation, since no oscillation in the guided signal is detected. The SPP propagation length at all three evaluated wavelengths was estimated to be approximately 10 μm, and although this is relative short, it is still long enough that the results shown in Fig. 5 demonstrates that electrospun nanofibers allow surface plasmons propagation and provide a good lateral confinement.
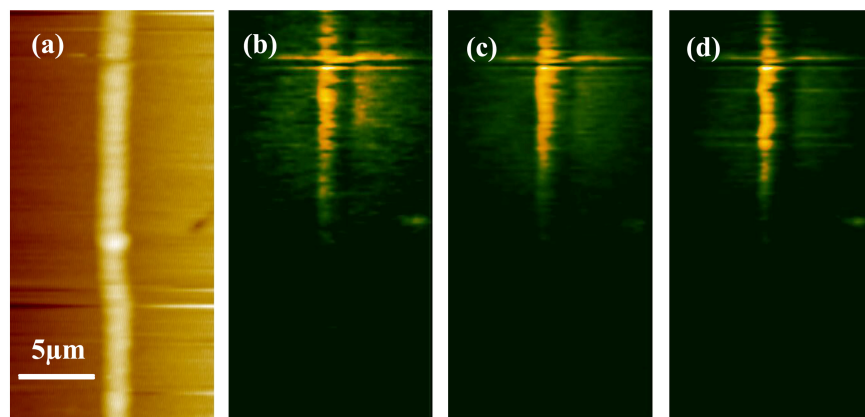

Fig. 5. Near field images of the propagating SPP wave demonstrating SPP waveguiding by the electrospun dielectric nanofiber. (a) Topography, (b) SNOM image for excitation with $\lambda = 1530nm$, (c) SNOM image for excitation with $\lambda = 1570nm$, (d) SNOM image for excitation with $\lambda = 1630nm$.

3.4 Discussion

It has been shown how electrospun nanofibers can be used as dielectric-loaded waveguides for surface plasmons excited directly inside the fibers. Although it is clear from the results

presented above that SPPs are guided in the fibers, the SPP propagation length is obviously very short. This can be explained by the fact that the dimensions of the waveguide are not ideal for long propagation distances. With the measured values, the propagation length is expected to be lower than 40 μm [10]. One way to improve the propagation length is to fabricate electrospun nanofibers with a more spherical cross section. This can e.g. be achieved by using a polymer solution with a higher polymer concentration for the electrospinning. Careful and systematic optimization of the spinning parameters like collector-tip distance, voltage and stage speed should in principle allow the fibers to be optimized for waveguiding SPPs of a given energy. Deposition of nanofibers by NFES is very fast and it is straight forward to add e.g. dye molecules or quantum dots [17] to the polymer solution before spinning and thereby electrospin polymer fibers with molecular dyes or quantum dots embedded. Therefore, NFES of DLSPPWs could be a very promising technique for e.g. testing of new dyes or nanoparticles for SPP amplification or loss compensation by stimulated emission. As a step forward in the fabrication of higher performance plasmonic waveguides by electrospinning, it could also be very interesting to use NFES to fabricate and investigate hybrid waveguides similar to those suggested by Oulton *et.al* [18].

4. Conclusion

It has been demonstrated that dielectric-loaded SPP waveguides can be fabricated using near-field electrospinning. This fabrication technique is very fast compared with traditional lithographic techniques. Therefore, electrospinning of dielectric loaded SPP waveguides could be a very promising technique for prototyping and testing of new SPP circuit designs, as well as for applications that require additives like quantum dots or dye molecules to be embedded into the waveguides, which is easy to accomplish using electrospinning. For this reason, this technique can be considered a step forward with regards to fabrication and testing of new plasmonic devices.

Acknowledgments