

# Design and Fabrication of Microfiber Containing Gold Nanoparticles

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**Abstract**—We present a simple fabrication method for embedding gold nanoparticles (GNPs) in a microfiber with two main advantages. The GNPs are positioned within the microfiber securing maximum enhancement of the electrical field and protection of the GNPs from the surroundings; moreover incoupling losses to the microfiber are reduced significantly by integrating a single mode fiber in the device. The average enhancement factor of the electric field within one unit cell of the microfiber due to the GNPs is estimated to 17.4. This enhancement leads to an enhanced Kerr effect near the plasmon resonance frequency. The fabrication method is demonstrated without GNPs.

## I. INTRODUCTION

Fiber-based devices are considered thoroughly within the field of optical communication [1, 2]. These can easily be integrated in optical systems, coupling losses minimized, and the size of the devices can be reduced, making packaging and reproducibility more simple and accessible. A microstructured fiber defined by having a diameter on the order of micrometers, referred to as microfiber, often both have high dispersion and high nonlinearity together with low loss and tight confinement of the field [3]. Therefore constructing optical devices with the use of microfibers has exciting possibilities [1]. Gold nanoparticles (GNPs) have a strong frequency dependent and reversible photo response, due to the particle size and shape dependent plasmon resonance frequency [2, 4, 5, 6]. This implies that a field sent through a fiber containing GNPs, will be enhanced, if the frequency corresponds to the resonance frequency of the GNPs.

In this paper we consider a simple fabrication method for embedding GNPs into a microfiber. Our fabrication method concerns a single mode fiber (SMF), which is uncoated, covered with GNPs, and then put into a capillary tube. Afterwards the fiber is tapered into a microfiber. This allows for the GNPs to be positioned within the microfiber yielding largest possible field enhancement, protecting them from the surroundings, and significantly reduce the coupling losses, since a SMF is integrated in the device. The average electric field enhancement factor in one unit cell of the microfiber is estimated to 17.4. This enhancement leads to an enhanced Kerr effect near the plasmon resonance frequency [7]. This allows for a microfiber containing GNPs to be used as an

optical switch [1]. The method is demonstrated by fabrication of a microfiber without GNPs.

## II. FABRICATION METHOD

The coating of a standard SMF with the dimensions 8/125  $\mu\text{m}$  is removed for a length of approximately 20 cm by a pair of pliers suited for uncoating. The SMF is put into a solvent, NanoXact Gold [8], containing GNPs of the desired size, leading to a well-defined resonance frequency. The GNPs will bind to the fiber by the silane coupling agent (3-aminopropyl)trimethoxysilane (APTMS) [9] and cover a fiber length of approximately 10 cm, see Fig. 1. The size of GNPs can be controlled, and thereby is the resonance frequency also controlled [2, 4, 5].

In order to achieve the desired design of having GNPs inside a microfiber, the SMF is put into a capillary tube having an outer and inner diameter of 375  $\mu\text{m}$  and 150  $\mu\text{m}$  respectively, this is shown schematically in Fig. 1 and Fig. 2. The difference in the inner diameter of the capillary tube and the outer diameter of the SMF introduce an air gap of 12.5  $\mu\text{m}$  around the SMF inside the capillary tube, if they are concentric. The size of the GNPs can be ignored. However it is found that this air gap does not conflict with the tapering process.

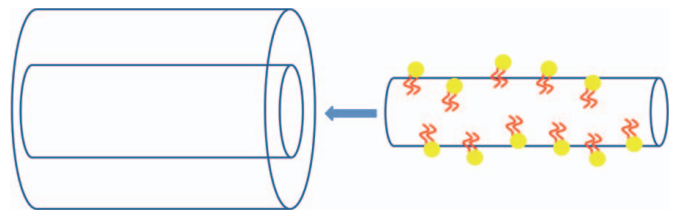


Fig. 1: The single mode fiber (8/125) covered with gold nanoparticles (scaled up in the figure) is put into a capillary tube (150/375).

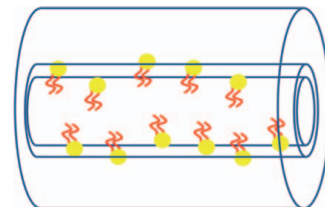


Fig. 2: The total fiber before tapering. The air gap between the single mode fiber and the capillary tube, and the gold nanoparticles are enlarged.

The total fiber is tapered by the flame-drawing method, where the fiber is fastened to a stage at one end and to a mechanical drawer at the other end. A bunsen burner is put underneath the fiber after which the mechanical drawer draws the fiber into a microfiber with a diameter of 1-2  $\mu\text{m}$  and a length of the tapered region of approximately 5 cm. A tapering of the total fiber from a diameter 375  $\mu\text{m}$  to 1-2  $\mu\text{m}$  will ensure that the GNPs will be placed close to the centre in the tapered region. Also, the field will be well confined inside the tapered region with a large intensity. This ensures largest possible field enhancement created by the GNPs.

The advantage of putting a SMF into a capillary tube and then taper it, is that the SMF can be used to couple light into the tapered region, without the use of splicing the device together with another fiber, since it is already connected. This lowers the coupling loss significantly.

### III. ESTIMATION OF FIELD ENHANCEMENT

We estimate the average enhancement factor of the electric field within one unit cell of the tapered fiber containing GNPs.

The GNPs are spheres with a diameter of approximately 40 nm and we know that they will cover 80 % of the SMF after it has been put into the solvent containing GNPs. Thereby we can estimate the volume of one unit cell containing one GNP. It must be given by the volume per unit length of the total fiber divided by the number of GNPs within one unit length. We consider the unit cell to be a sphere with a GNP centered at origo. This gives the following radius,  $r_{\text{uc}}$ , of the unit cell, when we assume that the GNPs are equidistantly spaced:

$$r_{\text{uc}} = 480 \text{ nm}. \quad (1)$$

The electric field at the resonance frequency will be enhanced by some enhancement factor,  $A$ . This enhancement decrease exponentially as a function of distance from the GNP. Thereby is the resulting electric field,  $E_{\text{res}}$ , given by:

$$E_{\text{res}} = E_0 \left( A \exp[-\alpha(r + r_{\text{GNP}})] + 1 \right), \quad (2)$$

where  $E_0$  is the incoming electric field,  $\alpha$  is the attenuation coefficient,  $r_{\text{GNP}}$  is the GNP radius,  $r$  is the radial coordinate, and the last term secure a nonvanishing field. We assume no losses within the fiber. To find the average enhancement factor of electric field within one unit cell,  $\tilde{E}_{\text{avg}}$ , (2) is integrated over the unit cell and divided by the volume,  $V_{\text{uc}}$ .

$$\tilde{E}_{\text{avg}} = \frac{1}{V_{\text{uc}}} \int_0^{r_{\text{uc}}} E_{\text{res}}(r) dV \Leftrightarrow \quad (3)$$

$$\tilde{E}_{\text{avg}} = \frac{1}{V_{\text{uc}}} \int_0^{r_{\text{uc}}} E_0 \left( A \exp[-\alpha(r + r_{\text{GNP}})] + 1 \right) dV \Leftrightarrow \quad (4)$$

$$\frac{\tilde{E}_{\text{avg}}}{E_0} = \frac{4\pi}{V_{\text{uc}}} \int_0^{r_{\text{uc}}} \left( A \exp[-\alpha(r + r_{\text{GNP}})] + 1 \right) r^2 dr. \quad (5)$$

This expresses the average field enhancement factor caused by the GNPs embedded in the fiber.

The field will be 100 times enhanced at the surface of the GNP, therefore the enhancement factor can be assumed to be  $A = 100$  [6].  $\alpha$  is estimated by assuming that the enhancement of the resulting electric field will have decayed to  $E_{\text{res}}/e$  at  $r' =$

200 nm, i.e. 200 nm away from the GNP [5]. This yields:

$$\alpha = \frac{1}{r'} \ln \left( \frac{e^{-1} E_{\text{res}} / E_0 \Big|_{r=0} - 1}{E_{\text{res}} / E_0 \Big|_{r=0} - 1} \right) = 5.09 \mu\text{m}^{-1}. \quad (6)$$

Inserting  $A$  and  $\alpha$  in (5) yields a average field enhancement factor of:

$$\frac{\tilde{E}_{\text{avg}}}{E_0} = 17.4. \quad (7)$$

The electric field within each unit cell is enhanced by a factor of 17.4. This enhancement will lead to an enhanced Kerr effect in the tapered region, and thereby open up for the possibility to use the microfiber as an optical switch.

### IV. FABRICATION WITHOUT GOLD NANOPARTICLES

The fabrication process is carried out without GNPs in order to define a controlled process, after which the GNPs can be implemented. This is to reduce cost and time spent in the examination period for this fabrication method.

#### A. Assembling of Single Mode Fiber and Capillary Tube

The polymer coating is removed from the SMF for a length of approximately 20 cm. This method is straightforward, however it does leave behind some remains of coating on the fiber. The SMF and the capillary tube are secured in two stages, and the two fiber end facets are viewed in a microscope. This way the SMF can easily be put into the capillary tube. Fig. 3 and Fig. 4 show pictures taking by a microscope of the SMF within the capillary tube. Fig. 4 shows the end facet of the capillary tube with an uncoated SMF inside. The air gap between the SMF and the capillary tube is evident in the picture, and small grains of dirt are seen, especially on the SMF inside the capillary tube. These can be attributed to coating that was not properly removed and small grains of dust. At the end facet of the capillary tube some excess coating from the SMF is collected, clarifying that the pair of pliers not removes all coating.

#### B. Collapsing of the Total Fiber

Usually when a fiber is tapered it consists of a solid material often silica, and the tapering process is done by the usual flame drawing method.

The fiber to be tapered in this paper is more complicated, since it actually consists of a tube containing a fiber with an air gap between them. Therefore it is considered, if it is necessary to collapse the outer tube to the inner fiber before tapering, or if this step can be omitted. Omitting this step

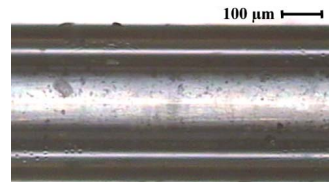


Fig. 3: Picture of the capillary tube containing the single mode fiber. Small particles of dust or unremoved coating are seen.

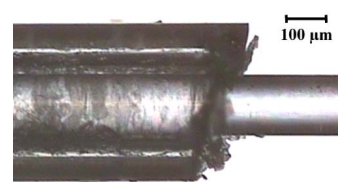


Fig. 4: Picture of the end facet of the capillary tube containing the single mode fiber. Some excess coating is seen at the end facet of the capillary tube.

would simplify the fabrication process. However one could imagine that the air gap between the fibers leads to tension within the total fiber, causing the tapering process to be impossible. The tension could cause the fiber to break in the tapering process, or simply make the fiber fragile and almost impossible to handle. In order to investigate if a collapsing of the fibers is necessary, the tapering process is carried out by first heating the total fiber until it becomes transparent, then taper the fiber, and consider the result in a microscope.

The total fiber is fastened in both ends and heated with the bunsen burner. It is important to have a well-controlled flame, since the total fiber should be heated a small region at a time. The centre region is heated first securing collapsing of the total fiber at the middle first, giving the air an escape possibility. If the capillary tube collapses to the SMF the radius will change. Comparing the cross section area of the total fiber with and without the air gap leads to a reduction in the diameter of approximately  $9\ \mu\text{m}$ . This is difficult to see with the naked eye, but can be detected in the microscope.

Fig. 5 and Fig. 6 show microscope pictures of the total fiber after heating. The border of the SMF and the inner surface of the capillary tube are still evident. Also, we see no reduction in the diameter of the total fiber, although this was predicted in case of collapsing. Therefore we assume that the fibers have not collapsed.

### C. Tapering of the Total Fiber

The capillary tube covering a 10 cm range of the uncoated SMF is secured in a stage at one end and a mechanical drawer at the other end. If the capillary tube is not covering the uncoated SMF it is simply too small to secure, making it impossible to taper the fiber. The total fiber is tapered for approximately 5 cm by continuing heating of the fibers, and then pulling it using the mechanical drawer.

Pictures of the fiber after the tapering process are seen in Fig. 7 and Fig. 8. Since it was not possible to collapse the fibers, the borders of the SMF and the inner surface of the capillary tube are still visible in Fig. 7, but it seems as a little region must have collapsed in the centre of the picture. This indicates that a collapsing can be achieved under the right conditions. In Fig. 8 the untapered end of the SMF is connected to a light source at a wavelength of 532 nm. The picture shows that the light is transmitted through the tapered region, which must indicate an intact fiber. This suggests that the tapering process can be carried out without collapsing the total fiber, even though there is an air gap between the SMF and the capillary tube.

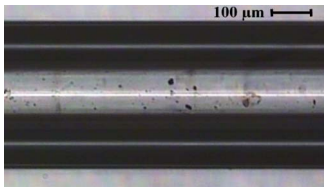


Fig. 5: Picture of the total fiber after heating. Borders from the air gap are still evident, consequently no collapsing of the fibers.

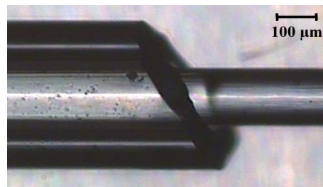


Fig. 6: Picture of the end facet of the capillary tube containing the single mode fiber after heating. The total fiber has not collapsed.

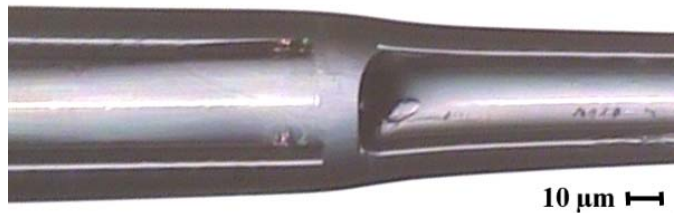


Fig. 7: The tapered total fiber. The boundaries of the single mode fiber and capillary tube are still visible, however at the middle it seems as the total fiber has collapsed.

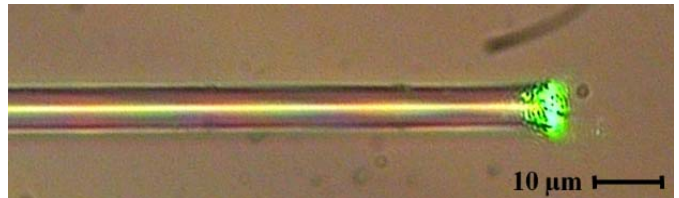


Fig. 8: Picture of the end facet of the total tapered fiber. The other end of the untapered single mode fiber is connected to a light source at a wavelength of 532 nm, yielding the green light output.

## V. CONCLUSION

We proposed a simple fabrication method for a microfiber containing GNPs. Two main advantages of this method are recognized. First the GNPs will be positioned within the fiber, leading to the highest possible enhancement of the incoming field and protection of the particles from the surroundings. Secondly the coupling losses of the device to an optical system are reduced significantly and incoupling is made easy. This is due to a SMF already being integrated in the device. We have estimated important parameters for the microfiber. The attenuation coefficient of the electric field is estimated to  $5.09\ \mu\text{m}^{-1}$ , by considered a fiber unit cell with one GNP inside and realizing that the field at the plasmon resonance frequency will decay exponentially as a function of distance from the GNP. Also, we have estimated the average enhancement factor of the electric field within one unit cell to 17.4. Lastly the fabrication method was carried out without GNPs. It was recognized that the total fiber could be tapered without collapsing the capillary tube on to the SMF, while maintaining guidance of light.

### FURTHER WORK

The microfibers containing GNPs will be fabricated during the fall 2010 at the Network Technology Research Centre at Nanyang Technological University. The absorption spectra will be measured to verify the effect of the GNPs [4, 7].

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