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Letter

Generating micropatterns onto the core of an optical fiber end with nanoparticles using fiber modes

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Abstract

In this paper we report an experimental study to generate micropatterns of nanoparticles using modes that propagate into optical fiber and the photodeposition technique. The different modes for instance LP_{01} , LP_{11} , LP_{21} and TM_{01} are obtained by performing a mechanical adjustment in an experimental setup. Subsequently, we placed the optical fiber end into a colloidal solution to adhere the nanoparticles on the core of the optical fiber end. The colloidal solution is composed by nanoparticles, such as gold, silver, zinc or single wall carbon nanotubes suspended in ethanol. The experimental results show that it is possible to obtain microscale patterning of nanoparticles in areas less than $10\ \mu\text{m}$ (diameter of optical fiber core). Furthermore, these micropatterns get the shape of the transversal mode that is propagated in the optical fiber. To the best of our knowledge, generating micropatterns onto an optical fiber end using fiber modes is demonstrated for the first time. The ability to pattern the optical fiber end with nanoparticles could enable several applications, for instance in the sensing based on localized surface plasmon resonance or in the manipulation of nano or micro-objects using micro-hotspots or temperature gradients.

Keywords: nanoparticles, optical fiber, photodeposition, laser, fiber modes


(Some figures may appear in colour only in the online journal)

1. Introduction

Nowadays, nanoparticles have been widely researched due to their unique optical, mechanical and chemical properties. Often these properties are different from the properties of the same material on a macroscopic scale. A very important feature of

nanostructured materials is that their physical properties can be tuned by controlling their shape and size [1, 2]. The nanostructured materials as well as micropatterns of nanoparticles are widely used in the generation of optical sensors [3–5], manipulation of micro-objects through temperature gradients [6–8], and surface enhanced Raman scattering [9, 10].

Some techniques for generating micropatterns with nanoparticles onto optical fibers ends have been used, for example, photochemical deposition [9, 10], electron beam lithography or evaporation [3, 4, 11], nanoskiving [12] and photodeposition

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via laser [5, 6, 13–17]. Photochemical deposition is a complex process due to the preparation of the reaction solution; additionally, some reagents used to generate the reaction solution are toxic. Furthermore, with this technique it is only possible to create micropatterns with gold or silver nanoparticles. In addition, electron beam lithography or evaporation provides high resolution and arbitrary patterning but still requires high cost with low throughput. Nanoskiving technique includes a complicated process (soft lithography and thin-film deposition) to the manufacture arrays of nanostructures. The photodeposition via laser is very attracted as the only necessary instruments are: a laser, an optical fiber, a lens to couple the laser light to the fiber, and nanoparticles suspended in alcohol. Using this technique it is possible to immobilize nanoparticles on an optical fiber end (all the core is covered with nanoparticles) without generating any special micropattern [5, 6].

In this paper, we report an experimental study of the generation of micropatterns on the core of a single-mode optical fiber using the different optical modes that travel into optical fiber. These micropatterns of nanoparticles are immobilized onto the tip of the optical fiber using the photodeposition technique. In previous works we demonstrated the photodeposition of nanoparticles such as silver, single wall carbon nanotubes (SWCNTs) or zinc onto single-mode and multimode optical fibers ends. These nanoparticles completely covered the core of the fiber because the previous works mainly used the fundamental mode (in the case of a multimode optical fiber) [5, 6, 13–17]. It is well known that in a multimode optical fiber various modes can propagate. The order of the modes is related to the angle of incidence of the beam and the axis of the optical fiber [18, 19]. In this work we demonstrate experimentally that it is possible to deposit nanoparticles according to the transverse mode that propagates into optical fiber.

1.1. Fiber modes

Modes refer to the spatial distribution of the light propagating through an optical fiber. They maintain the same transverse distribution at all locations along the optical fiber axis. The modal fields generally depend on all three cylindrical polar coordinates, and have the separable forms:

$$\mathbf{E} = E_x(r, \phi, z)\hat{i} = E_{x0}(r, \phi) \exp(-i\beta z)\hat{i}, \quad (1)$$

$$\mathbf{H} = H_y(r, \phi, z)\hat{j} = H_{y0}(r, \phi) \exp(-i\beta z)\hat{j}, \quad (2)$$

where β denotes the axial propagation constant. The construction of the modal fields is such that E_x and H_y satisfy the wave equation, given by:

$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + (k^2 - \beta^2) \right] E_x = 0, \quad (3)$$

$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + (k^2 - \beta^2) \right] H_y = 0, \quad (4)$$

where $k^2 = \mu_0 \varepsilon \omega^2$ is the wavevector of light propagating in a medium with permittivity ε . In an optical fiber, guided modes

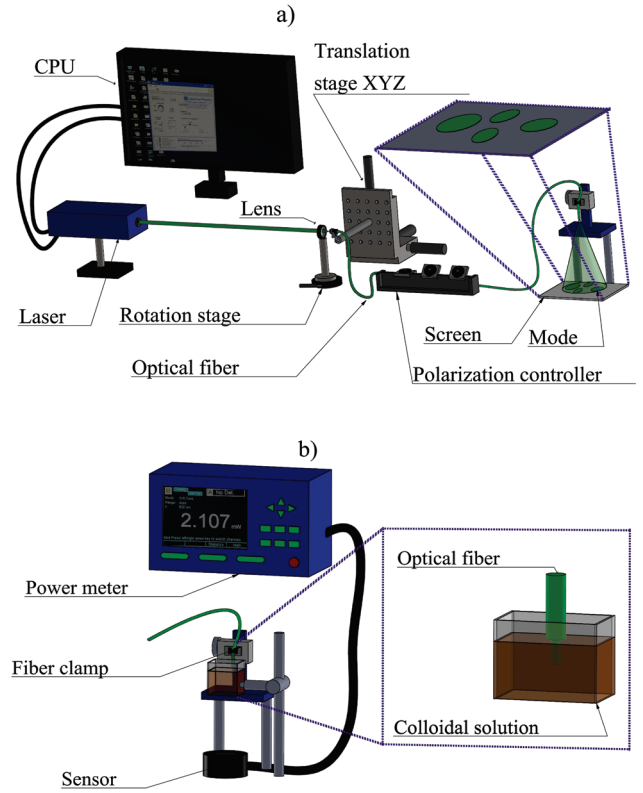


Figure 1. Experimental setup to (a) obtains LP_{lm} modes, and (b) photodeposition of micropatterns of nanoparticles on an optical fiber end.

in a core are solutions of a Bessel function of first kind and cladding modes are solutions of a modified Bessel function of second kind [18]. Typical optical fibers satisfy the paraxial approximation where the index contrast between core and cladding is very small. In such cases, it can be assumed that the fiber is weakly guiding; as such, the solutions of equations (3) and (4) are [18]:

$$E_x = E_0 J_l(ur/a) \cos(l\phi) \exp(-i\beta z), \quad r \leq a \quad (5)$$

$$H_y \approx E_x/\eta, \quad r \leq a \quad (6)$$

where a is the radius of the fiber optic core, l is known as the angular or azimuthal mode number for LP modes and must be an integer, J_l is ordinary Bessel function of the first kind of order l . Furthermore, $u = a(n_1^2 k_0^2 - \beta^2)^{1/2}$, where n_1 is the refractive index of the optical fiber core, η is the intrinsic impedance.

Experimentally, the LP modes are observed as intensity patterns, whose magnitude is given by [18]:

$$|\langle S \rangle| = \frac{1}{2} \text{Re} \{ E_x H_y^* \} = \frac{1}{2\eta} |E_x|^2. \quad (7)$$

The distribution of the intensity of the LP_{lm} modes in the fiber optic core is given by [16, 17]:

$$I_{lm} = I_0 J_l^2 \left(\frac{ur}{a} \right) \cos^2(l\phi), \quad (8)$$

where I_0 is the peak intensity maximum.

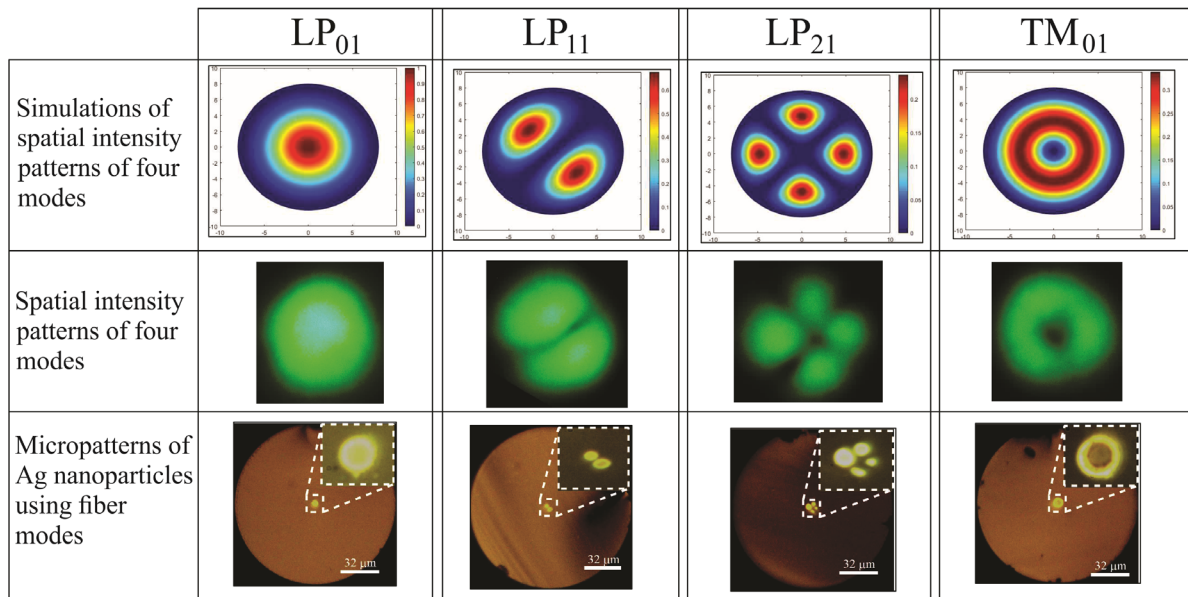


Figure 2. Fiber modes.

2. Setup

In our experiment to obtain linearly polarized modes, we used a pulsed laser (Mod. Explorer 532 NM from Spectra-Physics) emitting at a wavelength of $\lambda = 532$ nm with a frequency of 10 kHz and a pulse width < 15 ns. An aspheric lens was used to couple the laser light from the free space to the single-mode optical fiber. A translation stage *XYZ* and rotation stage were used to change the angle of incidence of the laser light with the axis of the optical fiber as shown in figure 1(a). In addition, we used a polarization controller and a single-mode optical fiber with an approximate length of 2 m and a cut-off wavelength of 870–970 nm. However, in the development of the experiment this optical fiber was considered as multimode because the excitation wavelength (532 nm) is much smaller than the cut-off wavelength. The modes were observed on a screen about 20 cm away from the tip of the fiber.

The photodeposition of micropatterns of silver nanoparticles onto an optical fiber end was carried out by placing the optical fiber tip into a colloidal solution (ethanol and nanoparticles such as silver, gold or zinc nanoparticles) as shown in figure 1(b).

The silver colloidal solution was prepared using 2 ml of ethanol and 0.3 mg of silver nanoparticles (whose sizes are less than 100 nm) and following the procedure reported in the [20]. The gold, zinc and single wall carbon nanotubes colloidal solutions were prepared by mixing 2 ml of ethanol with 0.5 mg of Zn NPs or 1 mg of Au NPs or 1 mg of SWCNTs and then homogenized using an ultrasonic bath for 5 min. The sizes of zinc nanoparticles are less than 20 μm whereas those gold nanoparticles are less than 5 μm . The single wall carbon nanotubes have an outside diameter between 1 and 2 nm, and a length between 5 and 20 μm .

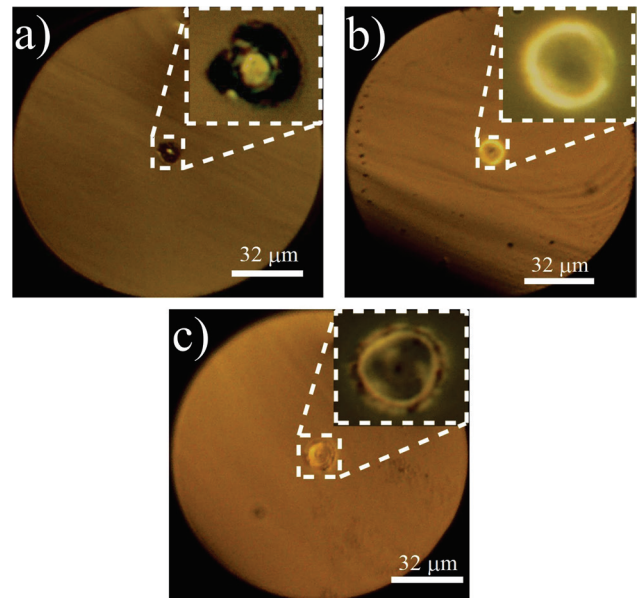


Figure 3. (a) Zinc, (b) gold and (c) single wall carbon nanostructures immobilized onto an optical fiber end using the TM₀₁ mode. The insets in the images are a magnification of the core of the optical fiber end.

3. Results and discussions

In previous studies, we demonstrated experimentally that it is possible to immobilize zinc nanoparticles or carbon nanotubes onto the single-mode optical fiber end [13–17]. Although we also immobilize silver nanoparticles onto a multi-mode optical fiber end, we always worked with the fundamental mode (LP₀₁) [5, 6]. For both cases, the nanoparticles always covered the entire core of the optical fiber.

Using equation (8) it is possible to obtain the spatial intensity patterns of several modes such as LP_{01} , LP_{11} , LP_{21} and TM_{01} . These images are showed in the first row of the figure 2. The excitation of the modes in the optical fiber was done manually by varying the angle of incidence of the light with two stages (translation and rotation) and changing the polarization state of the light with the polarization control plates. The modes projected on the observation screen were captured using a 14 Mpx cellphone camera; these images can be seen in the second row of figure 2. Once the desired mode is obtained, the tip of the fiber is immersed in the colloidal solution as shown in figure 1(b).

The mechanism of particle deposition is a well-known phenomenon. Particles move towards the fiber end by phenomena such as photophoresis, radiative pressure, and convection effects [8]. Therefore particles close to the core of the optical fiber end are adhered to it. This adherence is produced by particle interactions through a double layer repulsion and London attraction force [17, 21]. The average power at the output of the optical fiber is continuously monitored and the laser is turned off when the nanoparticles cause attenuation in the optical power of approximately 1.2 dB. This attenuation is provoked by scattering and absorption in the nanoparticles. The threshold energy for the immobilization of the silver nanoparticles in the optical fiber (considering the fundamental mode LP_{01}) is 15 μJ per pulse. Images obtained with an optical microscope of the micropatterns of silver nanoparticles onto an optical fiber end are shown in the third row of figure 2. It is important to mention that the spatial intensity for each pattern (optical mode) must be identical so that the photodeposited nanoparticles on the tip of the optical fiber have the same appearance as that of the optical mode.

The generation of micropatterns on the end of an optical fiber is also possible with another type of nanoparticles such as gold, zinc and single wall carbon nanotubes. Figure 3 shows images obtained with an optical microscope of these nanoparticles immobilized at the fiber end. The micropattern observed was obtained with the optical mode TM_{01} . Therefore, we believe that is possible to immobilize micropatterns onto an optical fiber end, considering any type of nanoparticles as long as they absorb in this case at 532 nm.

4. Conclusion

We have demonstrated an effective way to control the deposition and distribution of nanoparticles such as gold, silver, zinc or single wall carbon nanotubes onto the optical fiber end. The deposition of these nanoparticles is confined within the core area of the tip end, which corresponds to the diverse mode traveling into fiber. This technique is easy to carry out and its instrumentation is simple; it involves laser light, a lens, a translation and rotation stages, optical fiber and nanoparticles suspended in ethanol. The use of nanoparticles onto optical fibers is appropriate to generate micro-hotspots or temperature gradients, allowing the manipulation of nano or micro-objects. Additionally, nanoparticles onto an optical fiber end are used in optical fiber lasers and optical fiber sensors. Therefore nanoparticles adhered onto fibers ends

can improve the performance of the optical fiber laser or sensor.

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