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Fluorescent all-fiber light source based on micro-capillaries and on microstructured optical fibers terminated with a microbulb

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ABSTRACT

An integrated fiber-optic fluorescent light source compatible with photonic-crystal and hollow-core fibers is presented in this paper. We have studied the dependence of the fluorescence spectra on the length of a micro-capillary filled with Rhodamine 6G dissolved in glycerin. As the capillary, we used a standard fiber-optic glass ferrule with two parallel holes having an inner diameter of 125 μm. One of the holes was filled with fluorescing solution, while an SMF-28 fiber polished at 45° with aluminum coating was placed in the second hole to serve as a pumping fiber. As the solution was pumped by continuous-wave laser light at 532 nm, the fluorescence was captured by a microstructured optical fiber immersed in the filled hole. To prevent the solution from penetrating into this receiving fiber, its end was capped by molten borosilicate glass forming a ball lens. Combining the spectra of several fluorescent organic dyes can create a broadband light source compatible with optical fibers that could be used for the development of compact photonic-crystal and hollow-core fiber sensors.

1. Introduction

Microstructured optical fibers (MOFs), as a separate class of fibers, offer both light transmission and microfluidic transport. Based on their unique holey microstructure which enables them to be filled with fluids or solid materials, new sensors and functional fibers have been demonstrated [1–3]. The possibility for fluids control along micro-capillary channels inside the MOFs enables the manipulation of light which opens new opportunities for creation of tunable photonic crystal devices [4,5].

The use of long-period gratings (LPGs) both in photonic-crystal fibers (PCFs) [6] and in hollow-core fibers (HCFs) [7] has led to the creation of sensors with better characteristics than those employing conventional optical fibers. Most LPG-based sensors operate in the near infrared range which imposes the use of expensive detectors, while those working in the visible range [8,9] can use significantly cheaper detectors, resulting in reduced costs for the entire system.

The broadband light sources generally used in sensors, such as lamps and light emitting diodes, are bulky or have limited spectral width. As an alternative compatible with optical fibers, fluorescence light sources have been developed based on organic dyes [10-12]. Combining several appropriate fluorescent organic dye spectra makes it possible to increase the output spectral bandwidth and hence to cover the entire visible range.

With the present paper, the authors continue their previous studies on the development of broadband light sources compatible with SMF-28 fiber using organic dyes emitting in the visible range [13]. In order to take advantage of the possibilities offered by MOFs, we are now demonstrating compatibility with a miniature side-pumped fluorescent light source previously reported by us. A change of fluorescence spectra with the distance x between the receiving optical fiber and the excitation position has been observed. In our study we used both a PCF and an HCF as receiving fibers, capping them with a molten borosilicate glass before immersing them in fluorescent liquid. A simple theoretical analysis and calculation of the approximate distance between the start measurement position and the position in which more fluorescent light could be captured for each type of receiving fiber were made. The theoretical data obtained are in accordance with the experimental ones which confirm the assumptions made.

2. Experimental details

A schematic view of the experimental set-up with the components used is presented in Fig. 1. A glass ferrule – a standard fiber-optic component – is used as a micro-capillary structure for optical fiber alignment. This ferrule is a glass cylinder with an

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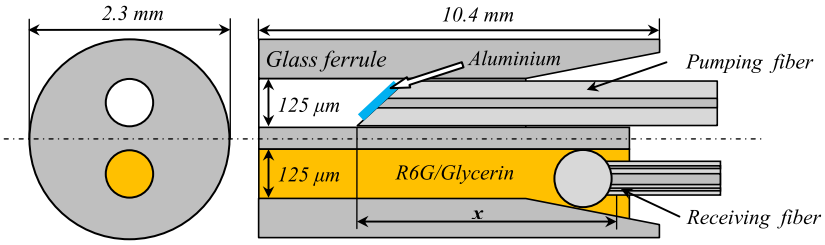

Fig. 1. Schematic view of the experimental set-up.

outside diameter of 2.3 mm, a length of 10.4 mm, and two parallel 125 μm holes along its length. The holes increase in diameter at one end in order to facilitate insertion of the optical fibers. The distance between the holes is approximately equal to their diameter.

The ferrule was cleaned with ethanol and allowed to dry, then one of the holes was filled with the prepared fluorescent solution. The solution was made by diluting an appropriate quantity of Rhodamine 6G (R6G) dissolved in ethanol and then mixed with glycerin to give the desired concentration after ethanol evaporation. The R6G concentration in the samples was 4.10^{-4} M. Pure ethanol and glycerin of 99.89% purity (sulfates 0.0002%, chlorides 0.0001%, heavy metals 5 ppm) were used for the analysis.

The receiving optical fiber was placed in the filled hole for registration of the fluorescent signal by a CCD spectrometer (AvaSpec 2048, Avantes) having a 200 μm slit. The sample mounted in the holder and the receiving fiber were fixed to a micropositioner having three linear displacements and two tilts. As receiving fibers, two types of experimental microstructured fibers were used: a PCF and an HCF, the end facets of which are shown in Fig. 2.

The PCF was a fused silica endlessly single-mode optical fiber with 125 μm outside diameter and microscopic air-filled holes 1.5 μm in diameter, placed around the 8 μm diameter solid core as shown in Fig. 2(a).

The HCF was made from a fused silica optical fiber with an outside diameter slightly greater than 125 μm, with a central air-filled hole 61 μm in diameter encircled by a ring of many voids around the rim of the hole (Fig. 2(b)).

The receiving fiber ends immersed in a fluorescent medium had been previously capped with borosilicate glass melted by a butane torch (see Fig. 3). The refractive index of the borosilicate glass is $n_{\text{sphere}}=1.52$. The ball lens thus formed on the tip of the fiber prevents penetration of the fluorescent solution into the receiving fibers. To check the quality of the capping, the tip of each receiving fiber was immersed in a drop of solution and side-illuminated by the pump light to allow for inspection under a microscope. Receiving fibers were only used after verification that no penetration of solution had occurred.

The fluorescent medium was side-pumped along the filled hole with the help of an SMF-28 optical fiber serving as a pumping fiber. This fiber was polished at 45° and placed inside the empty hole. The pumping fiber was polished using a FibrMet polishing machine for optical fibers. A thin aluminium film with a 99.999% purity was then deposited upon the polished facets using thermal evaporation in a vacuum chamber. This reflective aluminium coating directs the pump laser light towards the fluorescent solution.

The pumping fiber was coupled to a continuous-wave diode-pumped solid-state Nd:YAG laser emitting at $\lambda_{pump}=532$ nm. It was fixed in a syringe needle holder, then placed on a single-axis micropositioner. With the help of a micrometric screw on this micropositioner, the pumping fiber was moved along the hole to vary the distance x between the pumping and the receiving positions. The two micropositioners holding the pumping fiber and the receiving fiber were first mounted on an optical table and then placed under an optical microscope for observation.

3. Experimental results

The fluorescence spectrum was measured at steps of 0.127 mm over distance x in the range from 0 mm to 5.08 mm. Fig. 4(a and b) shows the fluorescence spectra for the PCF and HCF receiving fibers at different distances between the pumping and the receiving positions.

As seen in Fig. 2(b), the microstructure of an HCF has irregularities which spoil its symmetry and consequently decrease the possibility of a photonic band gap. In our case, the HCF functions more like a micro-capillary with a very thin wall. For this reason the fluorescence spectra for the HCF receiving fiber in Fig. 4(b) are similar to those from the PCF receiving fiber. This similarity does not affect the idea of combining the MOF and the light source into an integrated construction.

Fig. 5 shows the capped PCF receiving fiber when side-illuminated with a laser light. As can be seen (Fig. 5), the voids of microstructured area along the fiber length (for clarity see Fig. 2(a)), are not filled with borosilicate glass during the formation of the sphere after the melting process. Because of this, one can consider

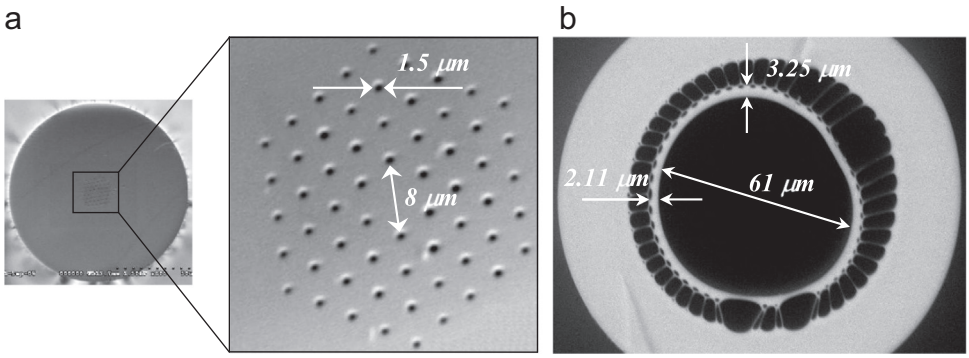

Fig. 2. Electron microscope pictures of end facets of the fibers used: (a) PCF and (b) HCF.