An Experimental Investigation on the Transient Characteristics of a Liquid-Filled Erbium-Doped Y-Shaped Microstructured Optical Fiber Laser

A. D. Guzmán-Chávez, A. Díez, J. L. Cruz, and M. V. Andrés*
Departamento de Física Aplicada-ICMUV, Universidad de Valencia, 46100 Burjassot, Spain
*e-mail: miguel.andres@uv.es

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Abstract—In this letter, we present an experimental characterization of a fiber laser made of a liquid-filled Erbium-doped Y-shaped MOF. It is found that the transient behavior of the laser emission varies when the refractive index of the liquid filling the holes is modified through its thermo-optic properties. This experimental work contributes to the development of special fiber light sources based on the interaction of the laser emission with liquids or gases.

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1. INTRODUCTION

Photonic crystal fibers (PCFs) and, more precisely, microstructured optical fibers (MOFs) are compatible with conventional fiber-optic technology and enable a strong interaction of light with liquids and gases. The filling of a MOF with a liquid or a gas, along tens of centimeters, can be carried out preserving the guidance of the light, this makes possible an efficient exploitation of different types of interactions of light with these materials, either in the linear regime through the real or the imaginary part of the filling medium, or in the nonlinear regime. Additionally, the most outstanding properties of MOFs can be preserved when they are filled with a liquid or a gas, such as special dispersion properties and photonic band gap (PBG) guidance. In fact, the filling of a MOF enables an extra control on these properties, like tuning of the dispersion properties [1] and tuning of the PBGs [2].

MOFs have demonstrated to be crucial for the development of supercontinuum and other special light sources based on non linear effects [3–7]. More specifically, liquid filled MOFs have an important role to play in the development of new fiber light sources [8, 9]. Supercontinuum generation has been demonstrated in water-core PCF [10]. A suspension of rutile particles in a rhodamine solution filling a hollow core PCF can give rise to a random fiber laser [11]. In addition, there are a number techniques and fiber components based on MOFs filled with liquids that it is worthwhile to mention, regarding the future development of new light sources, such as selective filling of air holes [11–13], switching the reflectivity of a fiber Bragg grating (FBG) with a thermo-optic effect [14] and generation and tuning of a long-wavelength cutoff for the fundamental mode [15]. In parallel, during the last years there has been an important development of fiber lasers based on Erbium and Ytterbium doped PCFs [16–18].

In this work, we present an experimental characterization of a fiber laser made of a liquid-filled Erbium-doped MOF. With this work we aim to contribute to the development of all-fiber light sources that combine laser emission with the interaction with liquids or gases, in order to produce special light sources. These systems could be particularly efficient in the exploitation of non linear effects in liquids or gases, taking advantage of the high energy density that can be reached within the cavity of a fiber laser, similarly to the supercontinuum sources recently proposed based on the intracavity insertion of a nonlinear PCF [19].

The fiber that we use in our experiments is a Y-shaped MOF that has an Erbium doped core, codoped with Germanium. The filling of this MOF with liquids is straightforward from one end of the fiber, due to the relatively large size of the holes. In addition, opening lateral holes is relatively affordable and would permit selective filling of the holes [20], in order to induce, for example, special birefringence properties. The fact that the core of the fiber is codoped with Ge enables the photoinscription of FBGs using standard techniques based on UV radiation of 244 nm [21] and, consequently, compact laser cavities could be prepared.

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

Figure 1 shows an SEM image of the Y-shaped MOF with erbium-germanium co-doped core. The MOF was fabricated using the conventional stack and draw technique [15]. Three capillaries of 2.6 mm outer diameter and 2.2 mm inner diameter were stacked
together to form a trefoil-shaped preform. An erbium-germanium co-doped silica rod was inserted in the interstitial hole between the three capillaries to form the core. The stack was inserted into a thick silica jacket and it was drawn to obtain the MOF. The outer diameter of the Y-shaped MOF is 130 µm and the core is about 4.5 µm across.

The erbium-germanium co-doped rod used to form the core was fabricated previously by stacking and drawing together a number of thin Er-doped silica wires and Ge-doped silica wires. The Er-doped wires were obtained from an Er-doped silica fiber preform with nominal concentration of Erbium ions of $1.15 \times 10^{26}$ ions/m$^3$. This preform was made by MCVD and it was formed of an Er-doped silica central region surrounded by a jacket of pure silica. The diameter ratio between doped and undoped sections was 2.5/5.0, and the refractive index (RI) step was $n = 0.0026$. The Ge-doped wires consisted on a section of a multimode Ge-doped silica fiber of 320 µm core diameter, 380 µm cladding diameter, and a numerical aperture of 0.29. In the MOF, the diameter of any doped region is much less than 1 µm, which is too small to form a waveguide. Therefore, it can be considered that the composite behaves as an effective index medium.

The absorption characteristics at ~978 nm and ~1.53 µm of the Y-shaped Erbium-doped MOF are shown in Fig. 2. They were measured by the cut-back technique using a low power white light source and an optical spectrum analyzer (OSA) with a resolution of 50 pm (ANDO AQ-6315A). The small-signal absorption coefficients are 2.6 cm$^{-1}$ @ 978 nm and 5.53 cm$^{-1}$ @ 1.53 µm.

The experimental arrangement of the fiber laser is schematically illustrated in Fig. 1. The gain was provided by a length of 120 cm of the MOF. The laser cavity was formed by two fiber Bragg gratings (FBG) written in standard photosensitive fiber that were fusion spliced to the MOF. Splice losses were about 1 dB. The reflectivity spectra of the FBGs are shown in Fig. 1. Peak reflectivity, Bragg wavelength, and 3-dB bandwidth for FBG1 and FBG2 are 98% and 89%, 1529.48 and 1529.53 nm, and 211 and 230 pm, respectively. The active fiber was pumped through a wavelength division multiplexer (WDM) by a high-power fibered semiconductor laser that provides a maximum power of 680 mW at 978 nm wavelength.

The holes of a section of 15 cm long of the MOF were filled with liquid methanol by capillary force and air pressure. Liquid methanol was chosen for these experiments because it has lower refractive index.