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Passively mode-locked erbium doped zirconia fiber laser using a nonlinear polarisation rotation technique

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ABSTRACT

A nonlinear polarization rotation (NPR) based mode-locked fiber laser is demonstrated using a 2 m long erbium-doped Zirconia–Yttria–Allumino Silicate fiber (EDZF) as the gain medium. The EDZF is drawn from a silica preform fabricated using the Modified Chemical Vapor Deposition (MCVD) method in which glass modifiers and nucleating agents are added using the solution doping technique. The fabricated EDZF has a core with dopant concentrations of 0.25 mol% of Al_2O_3, 2.10 mol% of ZrO_2 and 0.23 mol% of Er_2O_3, peak absorption of 22.0 dB/m at 978 nm and the fluorescence life-time of 10.86 ms. A stable picosecond laser is succesfully obtained with pulse width of 0.32 ps and the repetition rate of 50 MHz using a simple ring cavity.

1. Introduction

Recently, intensive research and development of Erbium doped fiber amplifiers (EDFAs) has spawned interest in other related areas including the various types of Erbium doped fiber lasers (EDFL) such as the mode-locked fiber lasers. For EDFAs, research efforts have focused on enhancing their performance, capability and compactness while reducing cost. In this regard, researchers are experimenting with new dopants such as alumina, phosphorus and new host materials such as telluride and bismuth [1–4]. The aim is to increase the erbium ion concentration in the fiber without incurring detrimental effects such as concentration quenching [5] and cluster formation [6]. However, these new materials are not without their drawbacks; Telluride and Bismuth based fibers cannot be easily spliced to conventional single-mode fibers (SMFs), thereby increasing the complexity of the amplifier and making it impractical for real-world applications. Hence, Zirconia has been seen as a highly promising candidate in the development of compact, high erbium concentration EDFAs [7,8]. Zirconia or ZrO_2 ions co-doped in silica fibers possess a high index of refraction of around 1.45 over the visible and near infrared spectrum. As such, ZrO_2 ions tend to exhibit wide emission and absorption bandwidths, as predicted by the Fuchtbauer–Ladenberg relationship [9,10] and Judd–Ofelt theory [11] and therefore can amplify more wavelength division multiplexing (WDM) channels than lower index materials. Furthermore, zirconia has excellent mechanical strength and is chemically corrosion resistant as well as being non-hygroscopic, and is easily spliced to SMFs while exhibiting excellent transmission in the visible and near infrared giving the zirconia doped EDFA practical applications in the real world.

Nowadays, mode-locked fiber lasers are the corner-stone of ultrafast optics which have been used widely especially in medical and industrial applications [12,13]. There are two techniques to obtain mode-locked fiber laser; actively or passively. Active mode-locked fiber laser can be achieved using the periodic modulation of the resonator losses or using the round-trip phase change. In passive mode-locked fiber laser, an intensity fluctuation acts in conjunction with the fiber nonlinearity to modulate the cavity loss without external control. In this paper, the fabrication and characterization of an Erbium Doped Zirconia–Yttria–Alumino Silicate Fiber (EDZF) are demonstrated. Then, the mode-locked EDZF laser is presented using one of the passive mode-locked techniques called the nonlinear polarization rotation (NPR). The principle of the NPR technique relies on the Kerr effect in a length of optical fiber in conjunction with polarizers to introduce artificial saturable absorber action and achieve pulse shortening [14].

2. Fabrication of EDZF

The EDZF is fabricated in three stages; Modified Chemical Vapor Deposition (MCVD), solution doping and drawing processes. In the first stage, a conventional silica preform is fabricated using the

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MCVD technique, whereby $SiCl_4$ and $POCl_3$ vapors are passed through a slowly rotating silica tube that is heated by an external burner. The burner heats the length of the tube as it rotates and, due to the high temperature, the chloride of $SiCl_4$ and $POCl_3$ vapors oxidizes to deposit a porous phospho–silica layer along the inner wall of the silica tube. The optimum deposition temperature range for the MCVD process is 1350–1400 °C, with a variation of the pre-sintering temperature from 1300 to 1450 °C. The fabricated silica tube, with its deposited porous phospho–silica layer, then undergoes a solution doping process using dopant precursors of suitable strength to obtain the optimized process parameters for making a fiber with a numerical aperture (NA) of approximately 0.17–0.20. The glass modifiers, ZrO_2, Y_2O_3, Al_2O_3 and Er_2O_3 are incorporated individually into the host matrix from the oxidation process of soaked layer with an alcoholic and water mixture of ratio of 1:5 containing suitable strength of salt of $ZrOCl_2.8H_2O$, $YCl_3.6H_2O$, $AlCl_3.6H_2O$ and $ErCl_3.6H_2O$ respectively through the solution doping technique. Small quantities of Y_2O_3 and P_2O_5 are also added to the glass matrix to act as nucleating agents, functioning to increase the phase separation of the Er_2O_3 doped micro-crystallites that will form in the core matrix of the optical fiber preform.

During the fabrication process, it is crucial to note that, in a bulk glass matrix, pure Zirconia exists in three distinct crystalline phases over different temperature ranges. At a very high temperature range, above 2350 °C, ZrO_2 has a cubic structure—whereas, at intermediate temperature range between 1170 and 2350 °C, a tetragonal structure is observed. At low temperature range, below approximately 1170 °C, ZrO_2 takes a monoclinic structure. The transformation of the crystalline structure from tetragonal to monoclinic is very rapid and is accompanied by a 3–5 percent volume increase. This rapid increase can result in extensive cracking in the material—as was observed in the doped core region of the preform after the fabrication—and is highly detrimental, as it destroys the mechanical properties of fabricated components during cooling. In order to overcome this problem, several oxides, such as MgO, CaO, and Y_2O_3 that dissolve in the Zirconia crystal structure can be used to slow down or eliminate these crystal structure changes; in this work a minute quantity of Y_2O_3 is used.

In the final stage of the fiber fabrication process, the fabricated preform that has undergone the solution doping process is annealed at 1100 °C for 3 h in a closed furnace, under heating and cooling rates of 20 °C/min, to generate Er_2O_3 doped ZrO_2 rich micro-crystalline particles. The resulting annealed preform is drawn into a fiber strand with a diameter of 125 ± 0.5 μm, using a conventional fiber drawing tower. During the drawing process, the preform (and the fiber obtained) is exposed to a temperature of around 2000 °C for only a few minutes. Due to the high cooling rate of the material and the melting temperature of the ZrO_2 crystals being above 2200 °C, the ZrO_2 nano-crystalline host is retained within the silica glass matrix. Both the primary and secondary coatings are applied to increase the tensile strength, as well as to reduce the moisture ingress from external sources. During the fiber drawing procedure, proper control of the fiber diameter, coating thickness and coating concentricity along the whole length of the fabricated fiber gives the optimization required for the production of a high quality optical fiber. The thickness and uniformity of both coatings are ensured by adjusting the flow pressure of the inlet gases into the primary and secondary coating resin vessels—during the drawing of the fiber, as well as by properly aligning the position of the primary and secondary coating cup units.

In this work an EDZF which contains 0.25 mol% of Al_2O_3, 2.10 mol% of ZrO_2 and 0.23 mol% of Er_2O_3 dopant concentrations was fabricated. The core of the fiber has a diameter of 10 μm with compositions of $SiO+Al_2O_3+P_2O_5-ZrO_2-Y_2O_3+Er_2O_3$. The fabricated fiber has an NA of 0.20, effective area of 75 μ^2 and core refractive index of 1.47. Fig. 1 shows the spectroscopic properties of the fabricated fiber; spectral attenuation and fluorescence decay curves. As shown in Fig. 1(a), the peak absorption of the fiber is measured to be 22.0 dB/m at 978 nm. The fluorescence life-time of the fiber is 10.86 ms as shown in Fig. 1(b).

3. Configuration of the mode-locked EDZF laser

Fig. 2 shows the experimental setup for a passively mode-locked EDZF laser, which is based on NPR. The principle of an NPR technique relies on the Kerr effect in a length of an optical fiber

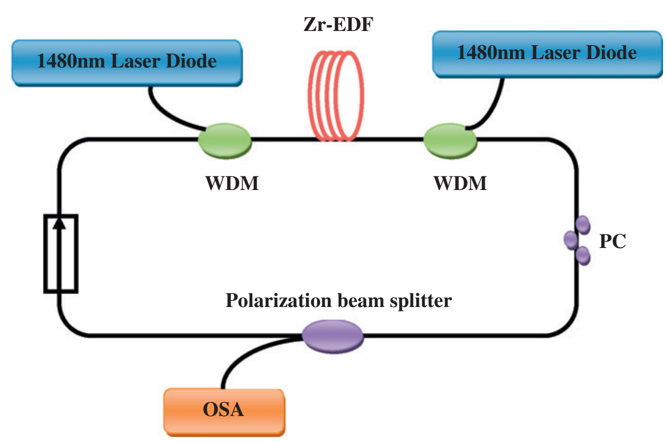

Fig. 2. Experiment setup for the proposed mode-locked EDZF laser.

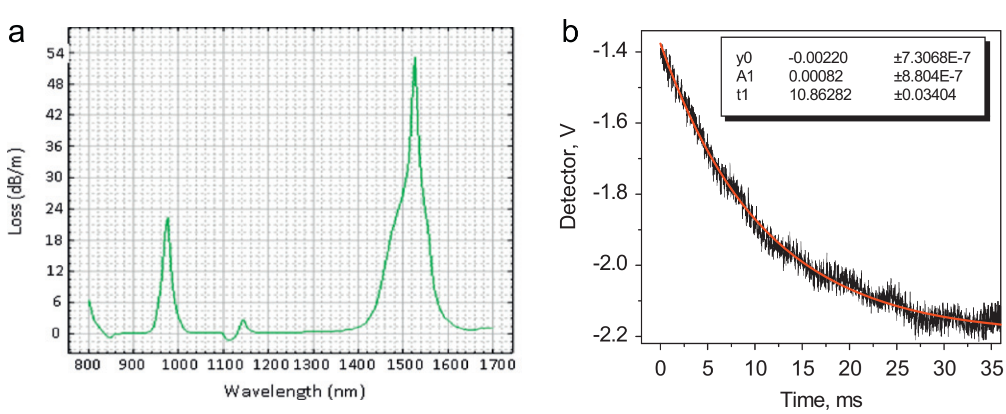

Fig. 1. Spectroscopic properties of the fabricated fiber (a) spectral attenuation and (b) fluorescence decay curves.