Nanosecond Pulse Erbium-Doped Fiber Laser based on Evanescent Field Interaction with Lutetium Oxide

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Abstract. The mechanism of evanescent field interaction is established between lutetium oxide (Lu2O3) and light on the surface of D-shaped optical fiber. The D-shaped optical fiber was prepared using rotating wheel technique with the improved two times polishing method. The side-polished fiber sample owns a remaining fiber diameter of 70 μm and polishing length of 1400 μm. Lutetium oxide was deposited onto the D-shaped optical fiber as a pulse initiator inside an erbium-doped fiber laser cavity. A Q-switched with operating wavelength of 1565 nm was generated. Stable pulses were recorded as the pump power raised from 146 to 162 mW with pulse width as short as 450 ns and repetition rate of 0.967 MHz. As the pump power varied, output power of 120 to 160 μW which corresponds to pulse energy of 124 to 166 pJ were obtained.

1. Introduction

Q-switched laser is one of the attractive techniques to compress and initiate the pulse in nanosecond to microsecond time domain. The avalanche applications of Q-switched laser including corrective eye surgery, tattoo removal technique and laser cutting technology had attracted enormous research effort in this area [1, 2]. Since the introduction of semiconductors saturable absorber mirrors (SESAMs) in 1992, the performance of Q-switched laser had been improved to several order of magnitude. SESAMs is able to generate pulses as short as 10 femtosecond due to its ability to produce regular pulse train in the laser cavity [3]. However, SESAMs possess narrow operating bandwidth which is in the range of 800 to 1600 nm, making it incompatible for longer near-infrared wavelength. The mechanism of pulses generation in SESAMs is also complex as it requires precise alignment of laser setup which will induce large signal loss inside the laser configuration. Therefore, an all-fiberized laser cavity is introduced as it manipulates the mechanism of saturable absorption inside the laser configuration. To date, few materials are utilized as a saturable absorber (SA) in the laser cavity.

Among materials, lutetium oxide (Lu2O3) exhibit nonlinear absorption of approximately 4%, non-saturable absorption of 13% and saturable intensity of 32.03 MW/cm² in 1.55 μm region. Therefore, lutetium oxide has been utilized as SA in erbium-doped fiber laser (EDFL) cavity for the generation of Q-switched and mode-locked [4, 5]. Lu2O3 which is used as a host material in laser, scintillator for X-ray imaging and production of ceramic possessed a wide absorption in near-infrared bandwidth [6-8]. Lu2O3 is proved to be an efficient additive to host materials (thulium, ytterbium and erbium) for rare-earth doped fiber laser as they are able to emit pulsed lasers in the 1-, 1.55- and 2-μm region [9-11]. In
addition, Lu₂O₃ has a high thermal expansion and high melting temperature which is important to withstand high intensity laser illumination from laser pump.

In recent years, Q-switched laser is generated via the incorporation of a thin film inside an all-fiberized laser cavity. Researchers are able to initiate ultrafast pulse laser in the range of ps to sub-fs pulse duration in EDFL cavity [12]. However, thin film possesses a low damage threshold as most of them are produced using a polymer matrix as a host such as polyvinyl alcohol (PVA) and poly-methyl methacrylate (PMMA). PVA and PMMA has a melting temperature of approximately 200 °C and 160 °C, respectively, making them vulnerable to high intensity laser pulses. Here, we demonstrate a D-shaped optical fiber coated lutetium oxide as a SA in EDFL cavity. Our SA device has a long nonlinear interaction length and high optical damage threshold which makes it superior for the generation of Q-switched [13]. Nanosecond pulse erbium-doped fiber laser is induced via evanescent field interaction between Lu₂O₃ and light on the surface of the D-shaped optical fiber.

2. Preparation and characterization of D-shaped fiber-Lu₂O₃

The D-shaped fiber was prepared using polishing wheel technique, similar manner to Ahmad et al. [14]. An amplified spontaneous emission (ASE) source was launched onto the single-mode optical fiber (SMF-28) with output power meter (Thorlabs) connected to another end. Two fiber holders were used to clamp both ends of the single-mode optical fiber, ensuring less vibration during polishing process. The waist region of the single-mode optical fiber was then placed onto the rotating wheel of the polisher. Approximately 2 mm long buffer was removed before polishing process. After 15 minutes of polishing process, a D-shaped fiber with 1400 μm long and 70 μm thick was produced.

The Lu₂O₃ solution was prepared by mixing isopropyl alcohol (IPA) with 99.99% pure Lu₂O₃ nanopowder purchased from Shanghai Xinglu Chemical Technology Co., Ltd. The process starts by stirring 50 mg of Lu₂O₃ nanopowder with 50 mL of IPA at room temperature for 24 hr. The mixture was then ultrasonicated for 6 hr at room temperature. A 3 μL of the prepared solution was drop onto D-shaped fiber for SA optimization. The linear absorption spectrum of the SA was shown in Figure 1 (a). The graph indicates ~1 dB absorption in 1565 nm wavelength, an optimum value for Q-switched generation. The modulation depth of prepared D-shaped fiber-Lu₂O₃ was measured using twin-balanced detector technique. Figure 1 (b) displayed a nonlinear absorption spectrum of SA device with 4% saturable absorption, 13% non-saturable absorption, and 32.03 MW/cm² saturable intensity.
Figure 1. Optical properties of D-shaped fiber-Lu$_2$O$_3$: (a) linear absorption spectrum within the span of 1200 to 1600 nm, and (b) nonlinear absorption profile measured using twin-balanced detector technique.

3. Erbium Doped Fiber Laser Ring Cavity

The laser cavity was setup as drawn in Figure 2. A laser diode pump with 980 nm wavelength was launched onto the 980/1550 nm wavelength division multiplexer (WDM) as a wavelength-dependent beam splitter. The output port of the WDM was further connected to a 2.8 m erbium-doped fiber as a gain medium. The gain medium has an absorption coefficient of 23 dB/m, a core diameter of 4 μm, a cladding diameter of 125 μm and a numerical aperture (NA) of 0.16. Next, the light was converged to an optical isolator thus ensure unilateral light generated. The light was then allowed to propagate towards the D-shaped fiber-Lu$_2$O$_3$ as a SA device. The SA was connected to the 90/10 optical coupler with 90% of light cycled back to a 1550 nm port of WDM. A 10% of light was used for analysis purposes. An optical spectrum analyzer (Anritsu, MS9710C) with resolution of 0.05 nm and an optical power meter (Thorlabs) was used to characterize the output signal. A 350 MHz digital oscilloscope (Gwinstek, GDS-3352) and 9 kHz-7.8 GHz radio frequency spectrum analyser (Anritsu, MS2683A) connected via a 1.2-GHz InGaAs photodetector were used for temporal characteristics analysis.

Figure 2. Experimental setup for nanosecond pulse generation in EDFL using Lu$_2$O$_3$-D-shaped fiber as saturable absorber.

4. Result and Discussion
A nanosecond pulse laser was generated at a threshold pump power of 146 mW. The optical spectrum analyzer measured a nanosecond pulse with a center wavelength of 1565 nm and a 3dB spectral bandwidth of 0.594 nm as depicted in Figure 3 (a). As the pump power raised from 146 to 162 mW, stable pulses observed. However, further increasing the input pump will causes the pulses to mitigate and eventually disappeared. Figure 3 (b) shows an oscilloscope trace of the nanosecond pulse generated at threshold pump power of 146 mW. The captured spectrum obtained a pulse width of 450 ns and a pulse period of 1034 ns. The signal was further analyzed using a radio frequency spectrum analyzer (RFSA) as shown in Figure 3 (c). The RFSA depicted a fundamental frequency with many harmonics within 6 MHz frequency span. The signal-to-noise ratio (SNR) of 46.24 dB was observed at a repetition rate of 0.967 MHz.

![Figure 3. Spectral and temporal performances of the Q-switched laser; (a) output spectrum, (b) typical oscilloscope trace, (c) and RF spectrum at 146 mW pump power.](image)

The signal was further investigated within the variation of multiple input pump power. The graph of repetition rate and pulse width against pump power was shown in Figure 4 (a). A nearly uniform pulse width and repetition rate was captured within 146 to 162 mW pump power. At a minimum attainable pump power, Q-switched generated obtained a pulse width of 450 ns and a repetition rate of 0.967 MHz. The graph of output power and pulse energy against pump power was also plotted in Figure 4 (b). A typical Q-switched behaviour was observed as the output power and pulse energy increased linearly with the increment of pump power. The Q-switched possesses an output power of 120 to 160 μW as the pump power raised within 146 to 162 mW. The laser generated exhibit pulse energy of 124 to 166 pJ within the same range of pump power.
5. Conclusion
We present nanosecond pulse generation with Lu2O3 deposited onto D-shaped fiber as a pulse generator for EDFL cavity. The D-shaped optical fiber prepared using a rotating wheel technique owns a polishing length of 1400 nm and a diameter of 70 μm. The mechanism of the evanescent field between Lu2O3 and light was exploited to generate Q-switched in the EDFL cavity. With the appropriate amount of Lu2O3 deposited onto D-shaped optical fiber, stable Q-switched initiated within 146 to 162 mW. The generated pulses exhibit the highest repetition rate of 0.967 MHz corresponds to the shortest pulse width of 450 ns. SNR measured was 46.24 dB indicating the stability of the laser. The maximum output power and pulse energy generated was 160 μW and 166 pJ, respectively, at a maximum attainable pump power of 162 mW.

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