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Sub-nanometer tuning of mode-locked pulse by mechanical strain on tapered fiber

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ABSTRACT

A tunable mode-locked fiber laser based on the non-linear polarization rotation (NPR) technique is proposed and demonstrated. A passively generated mode-locked output is obtained with a repetition rate of about 70 ns and an average output power of 0.7 mW, as well as a laser efficiency of 0.53%. The mode-locked pulses can be tuned over a span of 4.4 nm, from 1560.6 nm to 1556.2, corresponding to a stretching of the tapered fiber from 0 to 100 µm in 10 µm increments. The pulses have an average signal-to-noise ratio of about 41 dB in the frequency domain, indicating a highly stable mode-locked output. The system can repeat and reverse the generation of these pulses, a crucial criterion of many communications and sensing applications.

1. Introduction

The generation of ultrafast pulses in fiber lasers has become the key focus of substantial research efforts due to their potential applications in spectroscopy [1], biomedical research [2], telecommunications [3–5] and other avenues of scientific research [6]. These pulses, also known as mode-locked pulses, can be generated through various means both active and passive. Initial works on ultrafast pulses focused on the use of active mode-locking techniques, and while these techniques were able to generate the desired pulse output, various inherent factors limited their performance, including modulator bandwidth constraints as well as their general bulky size and high manufacturing cost [6,7].

In an effort to develop ultrafast laser sources that would be more suitable to the needs and requirements of the industry, research efforts have now turned towards passive mode-locking techniques to generate ultrafast pulses in fiber lasers. Passively mode-locked lasers are capable of generating the same output as their active counterparts, albeit with slightly less control over certain parameters. Nevertheless, passively mode-locked fiber lasers are able to provide the desired pulses in a compact, cost-effective and easy to operate package [6]. Mode-locking in fiber lasers can be accomplished by using saturable absorbers, such as graphene [8], transition metal dichalcogenides [9,10] and black phosphorus [11], or by exploiting certain optical phenomena such as nonlinear polarization rotation (NPR), nonlinear optical loop mirrors (NOLMs) and nonlinear amplifying loop mirrors (NALMs). Both approaches have their advantages and disadvantages; saturable absorbers are easy to fabricate and incorporate into laser cavities, while using the NPR, NOLM and NALM techniques allows for the generation of high power pulses and robust operation [8,12–15].

In this work, a mode-locked fiber laser based on the NPR technique is proposed and demonstrated. The laser also incorporates a novel tuning mechanism based on a tapered fiber, which allows for the mode-locked pulses to be tuned in the sub-nanometer scale, below 1.0 nm. The proposed method is simple to fabricate and operate, and thus highly cost effective in comparison to other tuning methods such as the use of gratings [16], exploiting fiber birefringence [17] or through the use of tunable filters [18–21]. In this regard, tapered fibers have already seen widespread use in multiple applications such as tunable fiber lasers [7,22,23], displacement sensors [24], refractive index sensors, strain sensors [25], supercontinuum generators [26] and microsphere resonator couplers [27]. Kieu et al. had already demonstrated that spectral response of the tapered fiber can be tuned by stretching the tapered fiber [22], while Fang et al. demonstrated a wavelength tunable thulium-doped mode locked pulse laser operating at around 2 µm with a tapered fiber was stretched for spectral tuning [7]. However in both cases, key issues arise, including the use of saturable absorbers that might be damaged during high power operation as well as tuning resolutions higher than 1.0 nm, making them undesirable for use in ITU optical channels.

2. Experimental set-up

The proposed mode-locked laser is built around an erbium doped fiber (EDF) as the primary gain medium and utilizes the NPR effect to generate the desired mode-locked output pulse. The setup of the proposed laser is shown in Fig. 1.

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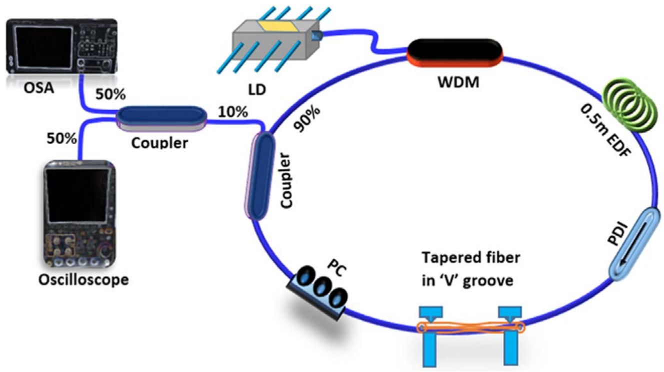

Fig. 1. Experimental set-up for proposed tunable mode-locked laser, where LD: Laser Diode, WDM: Wavelength Division Multiplexer, EDF: Erbium Doped Fiber, PDI: Polarization Dependent Isolator and PC: Polarization Controller.

The EDF used in this setup is a highly doped Liekki fiber, approximately 0.5 m long and obtained from nLight Photonics. The EDF is forward pumped by an Oclaro model LC96A74P laser diode (LD), which has an operating wavelength of 980 nm. The LD is connected to the EDF through the 980 nm port of a 980/1550 nm wavelength division multiplexer (WDM), with the common port of the WDM being spliced to the 0.5 m long EDF. The output of the EDF is now connected to a polarization dependent isolator (PDI), which is used to both maintain the polarization state of the signal propagating through the cavity, as well as ensuring unidirectional travel. The PDI is then connected to the tuning mechanism, which consists of the tapered fiber mounted on the V-groove of a Newport M-562 series XYZ linear stage. The linear stage has 4 "V" grooves in four clamps, and by adjusting the position of the clamps, the tapered fiber can be stretched or un-stretched, thus tuning the wavelength of the mode-locked pulse. Fig. 2 shows the image capture of the stages which are used to tune the mode-locked pulses travelling in the laser cavity.

The output from the tuning assembly is now guided towards the polarization controller (PC). The PC is typically used to control the polarization state of the signal propagating in the cavity, but in this setup it is used in combination with the PDI to induce the NPR effect and subsequently mode-locking, essentially acting as a saturable absorber. From the PC, the generated pulses continue to travel along

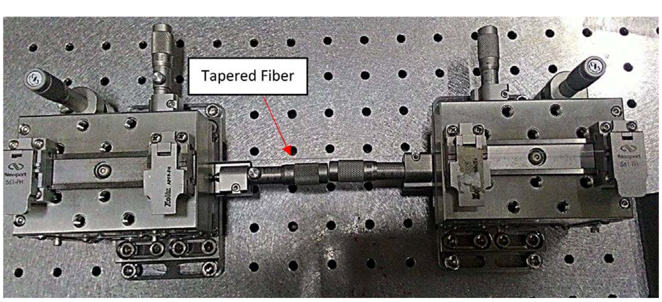

Fig. 2. Image of pulling-losing mechanism enabled linear XYZ stage to stretch the tapered fiber.

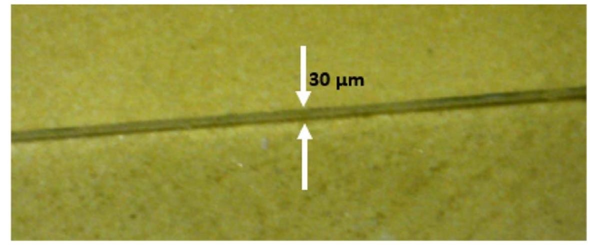

Fig. 4. Waist region of the fabricated tapered fiber.

the cavity, encountering a 90:10 coupler which is used extract a portion of the signal for analysis. The 90% port of the coupler connects to the 1550 nm port of the WDM, thus completing the laser cavity.

The tapered fiber used in the setup is able to tune the mode-locked spectrum generated by the cavity by changing the spectral response in the tapered fiber. The taper itself is fabricated from a single-mode-fiber (SMF-28) using the systematic flame brushing technique, in which the SMF-28 is heated and gently stretched simultaneously using a translation stage. The SMF-28 is prepared by first having its coating removed and the fiber cleaned using isopropyl alcohol. The cleaned fiber is then secured in place on the translation stage, which consists of a micro-controller, two stepper motors, one translational torch, one fixed fiber holder and a translational fiber holder. An amplified spontaneous emission (ASE) source is used to measure the transmission spectrum through the SMF-28 as it is being tapered, together with a Yokogawa AQ6370C optical spectrum analyser (OSA) with a spectral resolution 0.02 nm, as well as a Thorlabs D400FC 1 GHz InGaAs fiber optic photodetector and a PM100USB optical power meter (OPM). The setup used to fabricate the tapered fiber is illustrated in Fig. 3.

As the fiber is heated using a butane – oxygen mixed flame, the translation stages are also moved in steps of about 5.0 µm, thus stretching the fiber. The stretching process continues until a fiber waist size of about 30.0 µm is obtained, with an equivalent power loss of 3.6 dB. Fig. 4 shows the microscopic image of the taper waist, while Fig. 5 shows the ASE transmission spectrum before the tapering process starts, and also once it is completed.

The signal from the coupler, extracted by the 10% port of the 90:10 coupler, is divided again into two equal portions using a 50:50 coupler. One portion of the signal is used to analyse the optical characteristics of the mode-locked pulses, while the other portion of the signal is used to examine the pulse characteristics of the output. In addition to the OSA and OPM, measurements are also made using a Yokogawa DLM2054 oscilloscope (OSC) with a sampling rate of 2.5 GS/s, and an Anritsu MS2683A radio frequency analyser (RFSA), operating between 9.0 kHz 7.8 GHz in combination with an Alnair Labs HAC-200 auto-correlator. The total cavity length is estimated to be 14.5 m.

3. Results and discussion

The laser has a mode-locking threshold of approximately 60 mW, and subsequently kept constant at a pump power of 130 mW for the remainder of the work. Mode-locking is achieved as the light propa-

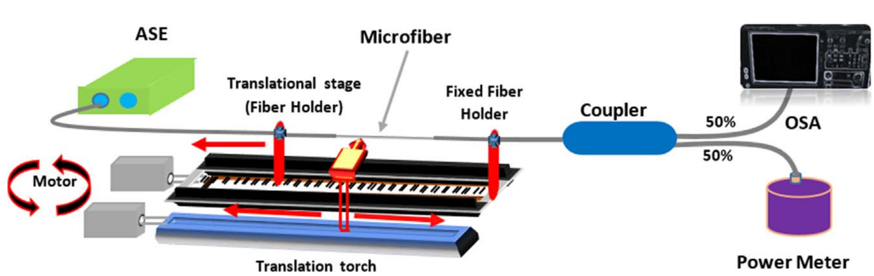

Fig. 3. Tapered fiber fabrication set-up.