Spectrum-, pulsewidth-, and wavelength-switchable all-fiber mode-locked Yb laser with fiber based birefringent filter

Y. S. Fedotov,[1,*] S. M. Kobtsev,[1] R. N. Arif,[2] A. G. Rozhin,[2] C. Mou,[2] and S. K. Turitsyn[2]

[1]Division of Laser Physics and Innovative Technologies, Novosibirsk State University, Novosibirk, 630090, Russia
[2]Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, United Kingdom
[*]fys@ngs.ru

Abstract: We examined methods of controlling the pulse duration, spectral width and wavelength of the output from an all-fiber Yb laser mode-locked by carbon nanotubes. It is shown that a segment of polarization maintaining (PM) fiber inserted into a standard single mode fiber based laser cavity can function as a spectral selective filter. Adjustment of the length of the PM fiber from 1 to 2 m led to a corresponding variation in the pulse duration from 2 to 3.8 ps, the spectral bandwidth of the laser output changes from 0.15 to 1.26 nm. Laser output wavelength detuning within up to 5 nm was demonstrated with a fixed length of the PM fiber by adjustment of the polarization controller.

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OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers

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1. Introduction

Laser mode locking by saturable absorbers (SA) based on single-wall carbon nanotubes (SWCNT) [1] has recently attracted a great deal of attention. An important advantage offered by SWCNT-based SA compared to semiconductor-based saturable absorber mirrors (SESAM) [2] is in their substantially simpler and cost efficient fabrication technology. In addition, over the last few years SWCNT have become more accessible and now feature diverse parameters. This stimulates research aimed both at (i) identification of the most efficient types of SWCNT and the methods of their synthesis, development of optimal matrices or substrates for fabrication of SWCNT-based SA, and (ii) finding the optimal operational conditions for application of SWCNT as SA [3–17]. A number of research groups studied the possibility of controlling the parameters of mode-locked lasers with SWCNT-

based SA [18–20]. In this work, we have investigated the control of spectral width and pulse duration of the SWCNT mode locked Yb fiber laser using fiber Lyot filter (FLF) [21].

It is important that there are fewer possibilities to control pulse duration in all-fiber mode-locked Ytterbium lasers in comparison with all-fiber mode-locked Erbium lasers, since there are no standard and commercially available non-expensive fibers with anomalous dispersion for the 1–1.1 µm spectral range. Compensation of positive dispersion in all-fiber Yb laser cavities is done either by using specialty fibers such as micro-structured fiber [22], long-period gratings in higher order mode fiber [23], tapered fiber [24], or hollow-core photonic bandgap fiber [25] or by means of chirped fiber Bragg gratings also acting as spectral filters [26, 27]. Although these methods provide possibility of control over pulse duration, they suffer from different drawbacks: e.g. effective splicing micro-structured fiber to standard fiber is still an issue; the tapered fiber core immediately exposed to the air may cause extra loss.

It is well known that intra-cavity spectral filtering can also provide for pulse-shaping of highly-chirped pulses [28, 29]. Filtering can be done using the chirped fiber Bragg gratings that have some technological limitations or free-space elements [28, 30] the latter approach is not fitting the all-fiber laser concept. Therefore, new all-fiber based filtering solutions are still in high demand. A promising approach to control pulse duration in all-fiber mode-locked Yb lasers is to utilize fiber based birefringent spectral filter [21], a fiber analogy to Lyot filter [31] which is used in conventional solid-state and dye-jet lasers for output wavelength tuning in a broad spectral range [32]. Similar approach is used in telecommunication systems [33] FLF described in Ref [30]. contains a length of PM fiber spliced with a second section of PM fiber at a certain angle between their principle axes (normally 45°). The second section of PM fiber propagates linear polarized light along its principle axis from a commercial polarizer. The length of the first PM fiber used in the fiber-based birefringent filter is analogous to the thickness of waveplate in a free-space Lyot filter and governs parameters of the filter. The transmittance of the classical Lyot filter [31] is given by Eq. (1):

$$T = \cos^2\left(\frac{\pi d\, \Delta n}{\lambda}\right) \tag{1}$$

where T is the filter transmittance, d stands for the thickness of the waveplate, Δn is the birefringence of the waveplate, and λ denotes the wavelength.

For FLF this equation might be transformed to [21]:

$$T = \cos^2\left(\frac{\pi L \Delta n}{\lambda}\right) \tag{2}$$

where L is the length of PM fiber, $\Delta n = n_{slow} - n_{fast}$ is the birefringence of PM fiber.

Transmittance of a FLF can be written as follows, taking into account variable splicing angle between axes of the two PM fibers:

$$T = 1 - \sin^2(2\theta)\sin^2\left(\frac{\pi L \Delta n}{\lambda}\right) \tag{3}$$

where T is the filter transmittance, θ is the angle between the principle axes of spliced PM fibers.

When a section of PM fiber is introduced into a laser cavity consisting of standard single-mode fibers (*i.e. no other PM* components), angle θ can be assumed as an arbitrary value. Usage of polarizer in the cavity (for example, in-line fiber polarizer or fiber polarization beam splitter etc.) or element with polarization dependent loss (PDL) (fused fiber coupler/ multiplexer etc.) leads to creation of Lyot filter in this configuration, even though the contrast of its transmission function may be different depending on the polarization of the input radiation. If the cavity includes a polarization controller (PC), the transmission function

contrast of the fiber-based Lyot filter is tunable. Based on Eq. (3), the calculated transmission spectra of a PM fiber based Lyot filter are shown in Fig. 1 indicating three different lengths of 1 m, 0.5 m and 2 m with individually spliced angles of 45°, 30° and 70°. In Fig. 1, during the calculation, the birefringence of the PM fiber is assumed to be 4.4×10^{-4}. It can be seen from Fig. 1 that the longer the PM fiber, the narrower the bandwidth. The different splicing angle indicates a different contrast ratio showing that 45° provides the highest contrast ratio.
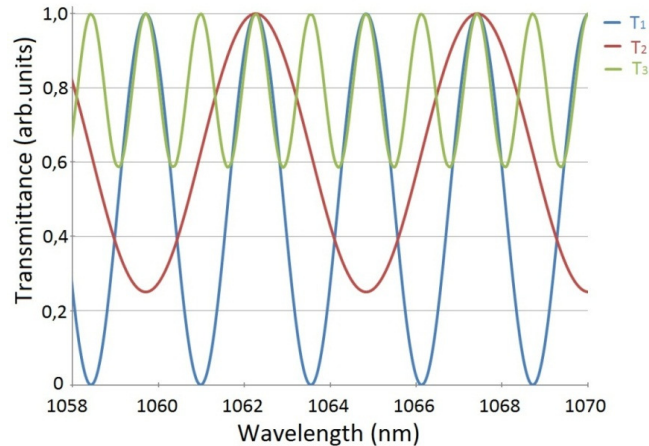
Fig. 1. Calculated transmission spectra of fiber-based Lyot filter with different splice angle of PM fibers. for T1, L = 1 m, θ = 45°; T2: L = 0,5 m, θ = 30° and T3: L = 2 m, θ = 70°. Note: Δn = 4.4×10^{-4} is used for calculation.

In this paper, we have proposed and demonstrated an all fiber mode locked Yb laser using FLF. The proposed fiber laser shows tunability of spectral width and pulse duration when mounted with different FLF. With a fixed FLF, switchable output central wavelength has also been obtained by tuning the PC.

2. Experiment set-up

The schematic diagram of our all-fiber Yb ring laser is shown in Fig. 2. The laser cavity was constructed using standard single-mode fibers based components. Approximately 30 cm single-mode Yb fiber with 1200 dB/km absorption at 975 nm was employed as the gain medium. Pump injection and single direction oscillation of the laser was performed by an integrated a wavelength division multiplexer with built-in optical isolator (IWDM). A 70/30 fused coupler was used to tap out the radiation from the ring resonator. The SA was represented by a polymer film containing SWCNT. One piece of PM fiber was added between the IWDM and SA to serve as a fiber based Lyot filter if cavity also consists of elements with PDL. In our cavity PDL was inserted by fused IWDM and fused coupler. An in-line PC was used to fine-tune the birefringence of the laser cavity, which leads to changes in mode-locked regime. The total length of the laser cavity is 2.7 m corresponding to a fundamental repetition rate of 77 MHz.
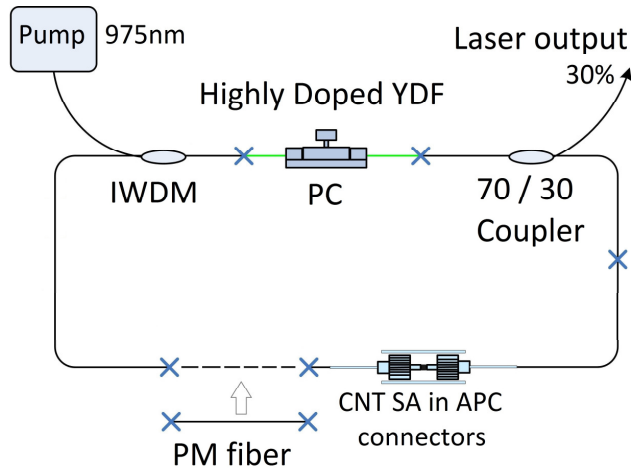
Fig. 2. Diagram of the all-fiber mode-locked Yb laser. Cross marks indicate fiber splices.

A SWCNT SA was prepared by using purified commercial CoMoCATs tubes (SWeNt CG100, Lot # 000-0012, SWeNT Inc) comprised of 90% of SWNTs of different chirality [34]. The 2 mg of tubes was dispersed in 25 ml of water containing 20 mg of sodium dodecylbenzene sulfonate (SDBS) surfactant using ultrasonication by NanoRuptor (Digenode) processor for one hour at 21 kHz and 250 W. Next the solution was subjected to ultracentrifugation for one hour at 25000 rpm at 17° C (Beckman Coulter Optima Max-XP, MLS 50 rotor) with the purpose to purify the solution and to remove the large SWCNT bundles. The resulting solution was mixed at ratio of 3:1 with a Polyvinyl Alcohol polymer. The solution then was slowly dried until a polymer film was formed.

To characterize precisely SNWT-absorption we measured pure PVA-film absorption and subtracted it from obtained data. The absorption spectrum of the SWCNT sample subtracted on absorption of PVA is shown in Fig. 3. Two near-IR bands centred at 1030 and 1160 nm, which typically indicate a presence of semiconducting SWCNTs with diameters ranging between 0.9 and 1.1 nm. The band at 1030nm has a FWHM approximately 100 nm and linear absorption around the working wavelength of the laser at 30% level. The fabricated film was clamped between two angled fiber connectors with index matching gel to minimize the Fresnel loss.
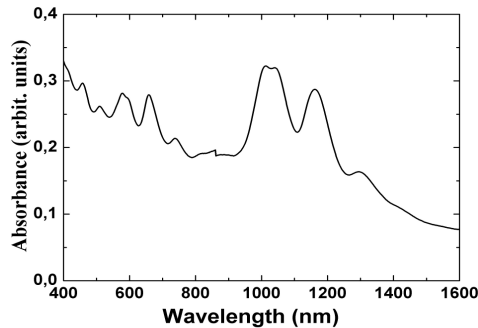

Fig. 3. Absorption spectrum of SWCNT sample

3. Results and discussion

Stable single-pulse mode-locked generation was achieved at 75 mW of pumping power. As the pumping level further increased, multi-pulsing was observed followed by Q-Switching. The average output power of the laser was 1–2 mW depending on the settings of the PC

which defines the properties of the fiber filter. Without the PM fiber in the cavity, the measured full width half maximum (FWHM) of the output spectrum is ~1.2 nm. Figures 4(a) and 4(b) demonstrate pulse trains and laser output spectrum in a configuration without the PM fiber. Generation around wavelength 1064 nm explained by transmittance of IWDM that we used.
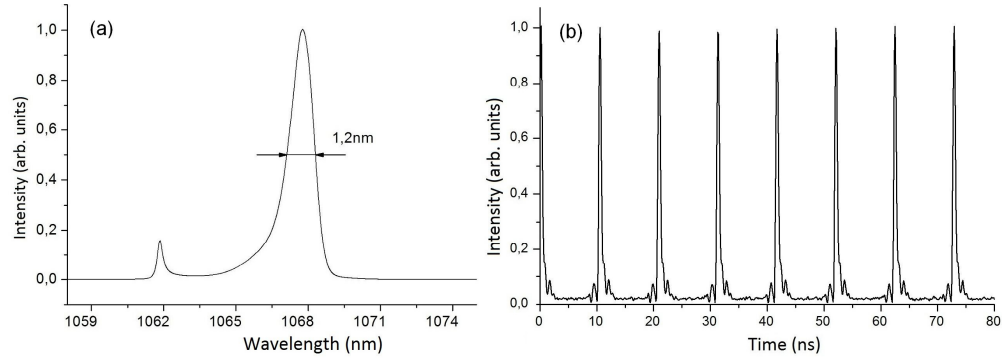

Fig. 4. (a) Laser output spectrum without PM fiber in the cavity. (b) Pulse train output from the laser in the configuration without PM fiber showing the repetition rate of 77 MHz with a pulse interval at ~13 ns.

To study the impacts of the fiber Lyot filter on the output spectrum and the pulse duration of the Yb fiber laser, the effects of various lengths of PM fiber were studied. The total cavity length was increased to 4.2 m and the replacement of FLF was done in the following way. After a section of PM fiber was spliced into the laser cavity, a piece of standard fiber of the same length was removed to maintain a constant cavity length and dispersion. By tuning the PC, modes of the laser could be easily locked. The output spectra of the laser with PM fiber sections 1, 1.5, and 2 m are presented in Figs. 6–8. It can be observed that at a fixed length of the PM fiber, tuning the PC allows tuning of the laser output wavelength. This tuning is particularly significant for the shortest length of the PM fiber (1 m). At the shortest length of the PM fiber, as predicted by our numerical calculations, we obtained the broadest output radiation spectra from the laser: 0.9–1.26 nm. As the PM fiber length increased to 2 m, the radiation spectrum contracted to 0.15–0.31 nm. Each curve in Figs. 5–7 corresponds to an output radiation spectrum measured in mode locked operation.
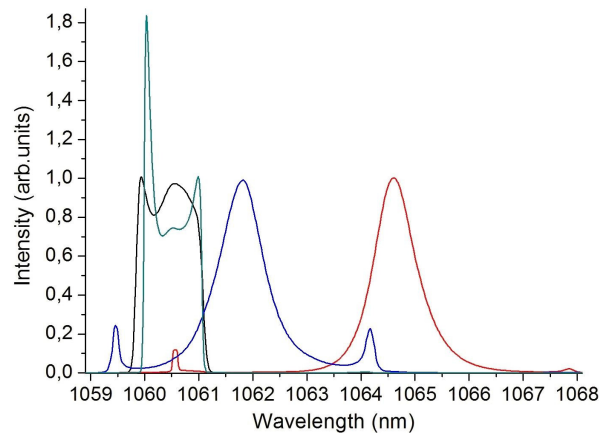

Fig. 5. Output spectra of the Yb laser mode locked at different settings of the PC showing different FWHM with 1 m PM fiber in the laser cavity.
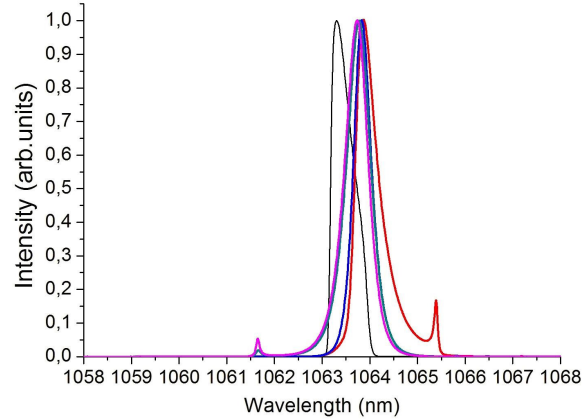
Fig. 6. Output spectra of the Yb laser mode locked at different settings of the PC showing different FWHM with 1.5 m PM fiber in the laser cavity.
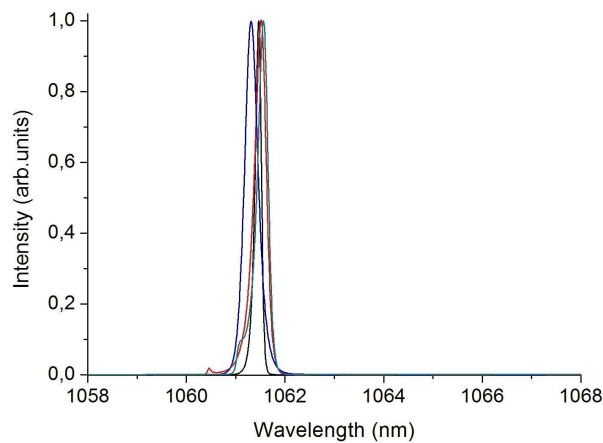

Fig. 7. Output spectra of the Yb laser mode locked at different settings of PC showing different FWHM with 2 m PM fiber in the laser cavity.

Experimental data in Fig. 7 clearly demonstrates the dependence of output spectral width upon the setting of the PC at a fixed length of the PM fiber within the laser cavity. This also corroborates the calculations presented in Fig. 1: adjustable contrast of the transmission function of the Lyot filter or its variable selectivity lead to changing spectral width of the laser output, which can be varied by a factor of > 2.

Thus, changing the PM fiber length within the cavity allows the control of the spectral width of the laser output in broad limits, whereas the adjustment of PC parameters at a fixed PM fiber length made it possible to detune the laser's output wavelength (at relatively short PM fiber length) and to fine-tune the width of the laser output spectrum with longer PM fiber in the resonator. The output power of the laser radiation reached 1.5 mW and the pulse repetition rate was 50 MHz.

To measure the pulse width, a scanning autocorrelator was used. For reliable signal the laser output was amplified by a fiber amplifier [35] up to an average power of 20 mW. Figures 8–10 illustrate the recorded pulse auto-correlation functions and their corresponding spectra for PM fibers of different length.

The auto-correlation function contrast indicates that the generated pulses have a certain amount of chirp. To estimate pulses duration, a theoretical analysis of the auto-correlation function was carried out with chirp calculation. The corresponding results are presented in Figs. 8–10.
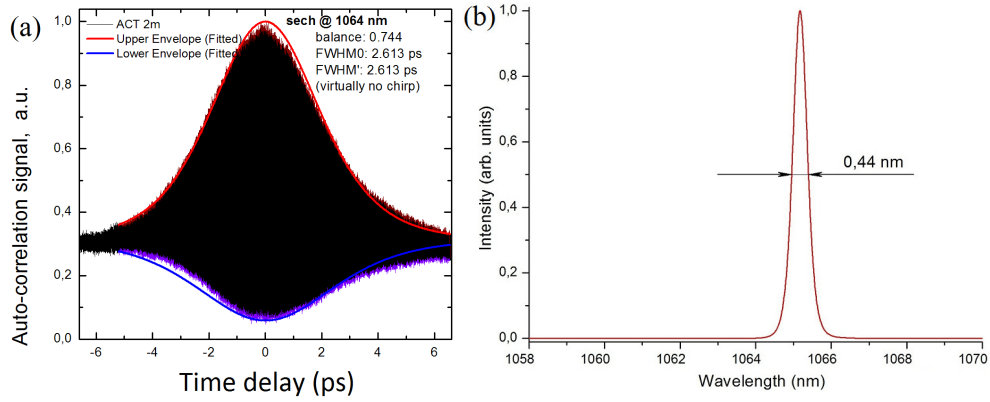
Fig. 8. Resonator with a 2-m PM fiber: experimental and theoretical (red and blue envelopes) pulse auto-correlation functions (a) and laser output spectrum (b).
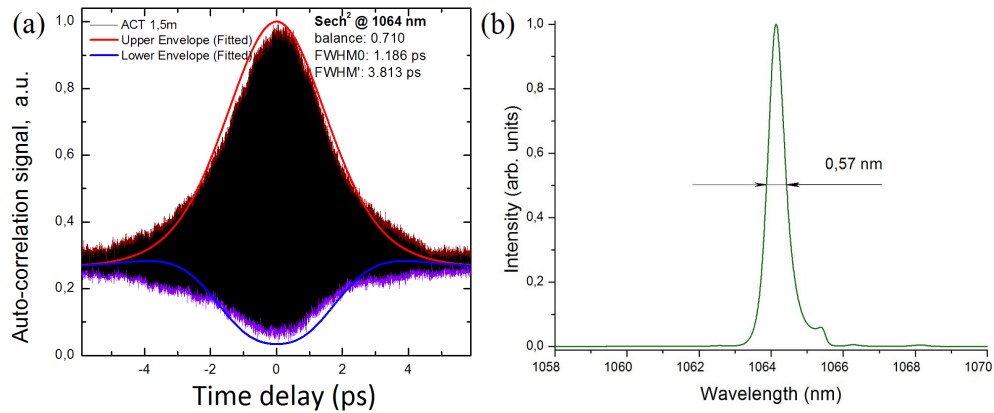

Fig. 9. Resonator with a 1.5-m PM fiber: experimental and theoretical (red and blue envelopes) pulse auto-correlation functions (a) and laser output spectrum (b).
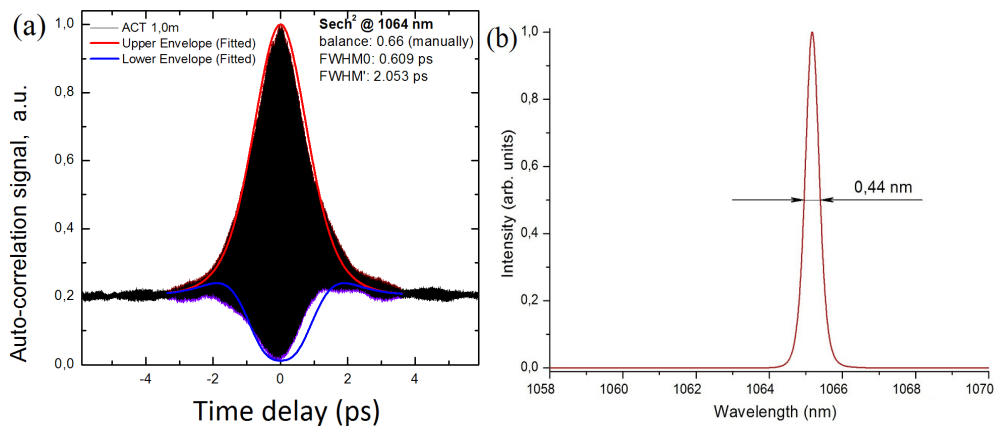

Fig. 10. Resonator with a 1-m PM fiber: experimental and theoretical (red and blue envelopes) pulse auto-correlation functions (a) and laser output spectrum (b).

It can be seen from these calculations that the birefringent filter allows controlling the chirp of the generated pulses. When a 2 m PM fiber is used in the laser cavity, the pulse

duration is 2.61 ps, which is very close to the transform limited value of 2.21 ps. For a 1.5 m PM fiber, the output pulses exhibited more chirp: their duration was 3.8 ps, whereas the spectrally limited duration was 1.71 ps. For a 1 m PM fiber, the pulse duration and the spectrally limited value were 2 and 1.2 ps respectively.

So, a PM fiber in a laser cavity can function as a spectral selective filter in a SWCNT mode locked Yb fiber laser. In the presence of a PC in such a cavity, the contrast of the filter's transmission function and the spectral position of its transmission peaks depend on the parameters of the PC.

4. Conclusion

We have demonstrated generation of ultra-short pulses with controlled duration, spectral width, and operation wavelength in an all-fiber laser with a SA based on SWCNT in PVA films within the wavelength range of 1060–1066 nm. The average output power of the laser was 1.5 mW at pulse repetition rate of 50 MHz. Utilization of a fiber Lyot filter made of different lengths of PM fiber in combination with a PC enables controlling the laser output spectrum width within the 0.15–1.25 nm range, the pulse duration within 2–3.8 ps, and detuning the laser output wavelength by up to 5 nm.

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