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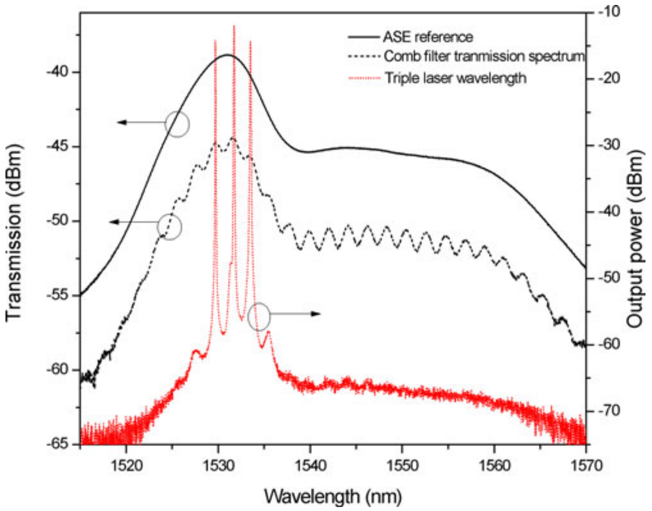

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Highly Stable, Tapered Fiber Filter-Assisted, Multiwavelength Q-Switched Er-Doped Fiber Laser Based on Tm-Ho Fiber as a Saturable Absorber

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Abstract: A multiwavelength Q-switched erbium-doped fiber ring laser based on a section of Tm-Ho codoped fiber as a saturable absorber, assisted by a tapered optical fiber filter to stabilize the lasing performance is reported. The tapered fiber structure acts as a comb filter that allows us simultaneous lasing wavelengths at 1529.69, 1531.74, and 1533.48 nm with high stability. By adjusting the pump power, optical pulses with repetition rates from 10.46 to 61.8 kHz were obtained. The maximum average output power was 27.61 mW, while 496.34 nJ for the maximum pulse energy. The fiber laser exhibits a power deviation of ± 0.376 dB, an OSNR of 54 dB, and a spectral width of lasing lines of 0.06 nm, with stable multiwavelength lasing.

Index Terms: Q-switched lasers, fiber lasers, erbium lasers.

1. Introduction

Q-switched fiber lasers, both passive and active, are pulsed optical sources with interesting properties such as robustness and compactness, high pulse energy, high repetition rates and in several cases with the capability to generate simultaneous wavelength lasing emission. These optical sources are becoming more demanded in applications as optical sensing, microfabrication or material processing, and others. The integration of these devices in all-fiber schemes also offers interesting features for the scientific community. In the last years, all-fiber, passive Q-switched, erbium-doped fiber lasers (EDFLs) have been reported using a diversity of materials as saturable absorbers (SAs), including for instance, carbon nanotubes [1]–[7], MoS_2, WS_2, $MoSe_2$, WSe_2, transition metal dichalcogenides [8]–[14], Fe_3O_4 nanoparticles [15]–[17], graphene [18]–[25], topological insulators [26]–[28] or semiconductor SA mirrors [29], [30]. All these SAs have different optical properties as fast recovery time, low optical damage threshold or high nonlinear optical

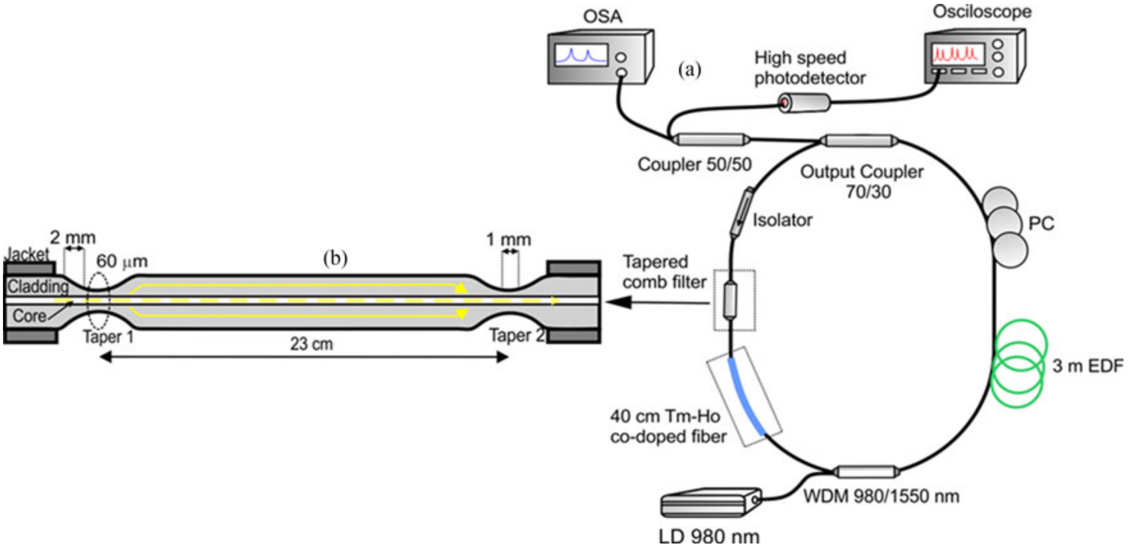


Fig. 1. (a) Experimental setup of the multi-wavelength Q-switched fiber ring laser, (b) comb fiber filter based on two concatenated tapered fibers with a separation length of 23 cm.

response that enables effective Q-switching operation of EDFLs with stable optical pulses, pulse repetition rates from tens to hundreds of kHz and high energy pulses.

Also recently, an important number of Q-switched fiber lasers operating in the optical C and L band have been experimentally demonstrated using sections of Tm-doped or Tm-Ho co-doped fiber as a fiber saturable absorbers (FSA). Essentially, the pioneers developing Er-doped Q-switched fiber lasers based on Thulium FSA were Tsai *et al.* and Kurkov *et al.* [31], [32]. They demonstrated optical pulses with repetition rates below 10 kHz and lasing emission between 1570-1580 nm. Lately, Tao *et al.* demonstrated Q-switching and Mode-locking of EDFLs using a section of Tm-Ho co-doped FSA, increasing several times the repetition rate of the optical pulses (in comparison with the use of Tm FSA), due to the high interaction between Tm and Ho ions and its temporal properties of absorption and ion relaxation [33], [34]. Furthermore, tunable Q-switched fiber laser based on Tm-Ho FSA was developed in a 38 nm wide band from 1535 nm to 1573 nm by using a Fabry-Perot filter [35]. More recently, multi-wavelength Q-switched fiber laser was obtained using the mode-beating effect created by the modal transmission characteristics between the 37 cm section of Tm-Ho co-doped FSA and the standard SMF-28 of the ring cavity, generating multiple lasing wavelengths in the range of 1545 nm to 1560 nm [36]. Also, dual wavelength, Q-switching and Mode-locking of EDFLs was demonstrated using 19 cm of Tm-Ho co-doped FSA and the insertion of 195 m of standard SMF in the cavity [37].

In the above described multi-wavelength Q-switched EDFLs based on Tm and Tm-Ho doped fibers, more work is needed as Tao *et al.* suggest in [36], in terms of wavelength stability or wavelength manipulation. Following this direction, a highly stable, multi-wavelength Q-switched EDFL based on a section of Tm-Ho as FSA is reported in this work, with the advantage of being assisted by a tapered filter structure which acts as a comb filter to enable a high temporal stability and multi-wavelength operation, maintaining the well-known Q-switched pulse characteristics reported in the above mentioned literature. To the best of our knowledge, this is the first time that a tapered fiber structure is used as a stabilizer of the lasing performance when a section of Tm-Ho doped fiber is used as a FSA in Q-switched fiber lasers.

2. Experimental Setup

The multi-wavelength Q-switched Er-doped fiber ring laser setup is depicted in Fig. 1(a). The system consists of 3 m of large-mode area Er-doped fiber laser (LIEKKI Er16-8/125) as the gain medium, which is pumped with a 980 nm laser diode (LD) through a wavelength division multiplexer (WDM).

An output coupler is added to the cavity to extract the 30% of the laser signal, while the remaining 70% feeds back the laser cavity. The extracted laser signal is divided by a 50/50 coupler to measure both temporal and wavelength response. The temporal response is measured employing an oscilloscope (Tektronix DPO7054) through a photodetector (Model DET08CFC InGaAs Thorlabs), while the lasing wavelength with an optical spectrum analyzer (OSA Anritsu MS9740A). The Q-switched optical pulses are generated splicing into the cavity a FSA, which consist of 40 cm of Tm-Ho single mode fiber (TH512 CorActive).

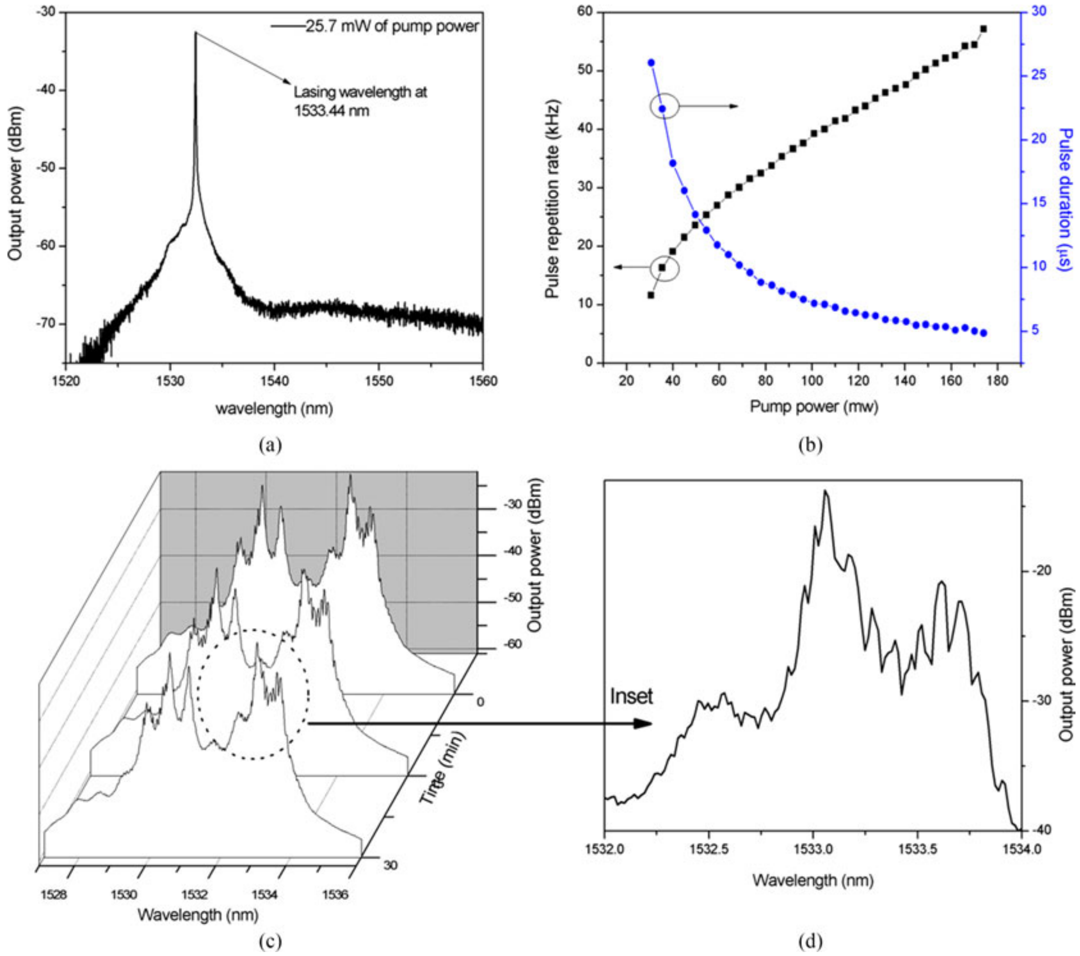
On the other hand, the tapered filter is composed of two quasi-abrupt tapered fiber sections fabricated on an SMF-28 with geometrical dimensions of 2 mm transition length, 1 mm waist length, 60 μm waist diameter and 23 cm of separation between tapers, manufactured in a GPX 300 Vytran glass processing system. Finally, an optical isolator and a polarization controller were included into the cavity, to ensure the unidirectional laser oscillation and to control the polarization state, respectively.

The optical absorption and ion relaxation system built between the Er-ions and the Tm-Ho co-doped FSA (and the intensive interaction between the Tm and Ho ions) is the principal mechanism for the generation of the Q-switched EDFL (explained in detail in the reference [34]). Initially, a first experiment of the Q-switched EDFL was done without the tapered comb filter. With this condition, the laser threshold is about 25.78 mW of pump power, and the laser wavelength is build up at 1533.44 nm, as can be seen in Fig. 2(a). At this pump power level, continuous wave regime is observed. The laser is generated at this wavelength as a result of the absorption properties of the Tm ions of the FSA, which preferably absorbs the long wavelengths the of Er-doped emission band, reshaping the spectrum and allowing to oscillate at its maximal gain, in this case, nearly 1530 nm. By pumping at 30.6 mW, stable Q-switched optical pulses are generated. The Fig. 2(b) illustrates the performance of the repetition rate and the pulse duration versus pump power, in where the obtained optical pulses vary from 11.6 kHz to 57.14 kHz and the pulse duration decreases from 26.05 μs to 4.86 μs to a maximum pump power of 174 mW.

Furthermore, beyond this pump level, the FSA is totally bleached, and the laser achieves the continuous-wave regime again. On the other hand, as the pump power is increased, the spectrum of the lasing wavelength becomes broader, generating unstable multi-wavelength emission due to the strong mode competition. The Fig. 2(c) shows the unstable multi-wavelength emission spectrum at 110 mW of pump power, scanned three times within an interval of 30 minutes, which fluctuates above $\pm$2.45 dB in power and 0.2 nm in wavelength shift.

3. Stable Multiwavelength Q-Switched Laser Operation

To overcome the wavelength lasing instabilities in the Q-switched regime, an optical tapered fiber filter was inserted into the laser cavity to mitigate the mode competition and build up stable multi-wavelength emission. The operation principle of the filter is based on the interference between the core and coupled cladding-modes. In the first transition taper, the fundamental core-mode is coupled to higher order cladding-modes and then acquires a phase delay in the length section between the two tapers, due to the difference in the refractive index of the core and the cladding. In the second transition taper, the cladding mode is back coupled to the core, creating in this manner a characteristic comb spectral pattern of interference. The spectral features such as the free spectral range (FSR), fringe visibility, and the insertion losses of the comb filter depends mainly on the geometrical dimensions of the tapers, and the separation length between them. Prior to its insertion into the cavity, the transmission spectrum of the fiber filter (dashed line in Fig. 3) was obtained employing the ASE source of the Er-doped fiber (straight line in Fig. 3) as a reference. The fringe visibility of the interferometer is $\sim$0.15, while the FSR is about 2.1 nm. The insertion loss of the filter is $\sim$3.3 dB. By adding the filter into the cavity, three lasing wavelengths at 1529.69 nm, 1531.74 nm, and 1533.48 nm are generated, shown in Fig. 3 at the red dotted line, (pumped with 110 mW). From this Fig. 3, it can be seen that the peaks of the laser wavelengths match the peaks of the transmission spectrum generated by the comb filter, as it was expected, showing an optical signal to noise ratio of 54 dB and 0.06 nm of spectral width of the lasing wavelengths.



(a) (b) (c) (d)

Fig. 2. (a) Laser emission at 1533.44 nm below the threshold of the Q-switched laser regime, (b) repetition rate and pulse width as a function of the optical pump power, (c) broadened lasing spectrum scanned three times within an interval of 30 minutes, (d) inset from the Fig. 2 (c) in a wavelength band from 1532 nm to 1534 nm.

On the other hand, the Q-switched optical pulses were characterized with the filter into the cavity. Initially, the Q-switching regime starts with a repetition rate of 10.64 kHz by pumping the cavity with 30.6 mW of launched pump power. Subsequently, the increment in the pump power increases the pulse repetition rate from 10.64 kHz to 61.8 kHz for a maximum pump level of 157.6 mW. Furthermore, the pulse duration or pulse width is decremented from 27.65 μs to 6.8 μs. The behaviors for both parameters are shown in Fig. 4, as a function of the pump power. Pumping the cavity above this level, the laser attains the continuous-wave oscillation. Moreover, Fig. 5 shows four samples of stable Q-switched train pulses, indicating the repetition rates at different levels of pump power (from 30.6 mW to 149 mW).

Besides, another important parameter of the Q-switched multi-wavelength fiber laser is the output power and the energy of the pulses, which are illustrated in the Fig. 6 as a function of the launched pump power. The maximum average output power obtained from this laser system in the Q-switched regime is $\sim$27.61 mW and exhibits an optical efficiency about 17.51%. Moreover, the maximum pulse energy achieved is 496.34 nJ at a repetition rate of 48.75 kHz and 136.1 mW of pump power.

Finally, in order to verify the multi-wavelength stability, the wavelength spectrum of the fiber laser was monitored over one hour taking samples every 5 minutes, while the cavity was constantly pumped at 110 mW. From Fig. 7(a), it can be observed high uniformity in the intensity of the multi-wavelength laser emission. Also, the maximum wavelength deviation is 0.03 nm, and its behavior is

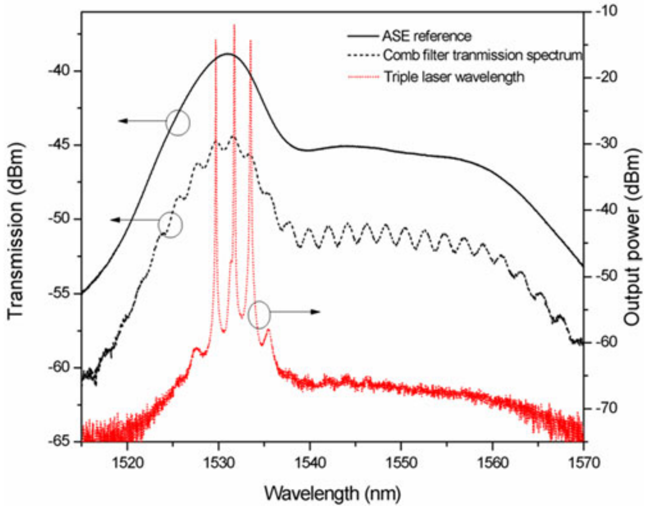


Fig. 3. The spectral transmission of the tapered comb fiber filter (dashed line) characterized employing the ASE light emission of the Er-doped fiber laser (straight line). The laser signal is build up in three lasing wavelengths, matching the peaks of the comb spectrum (red dotted line).

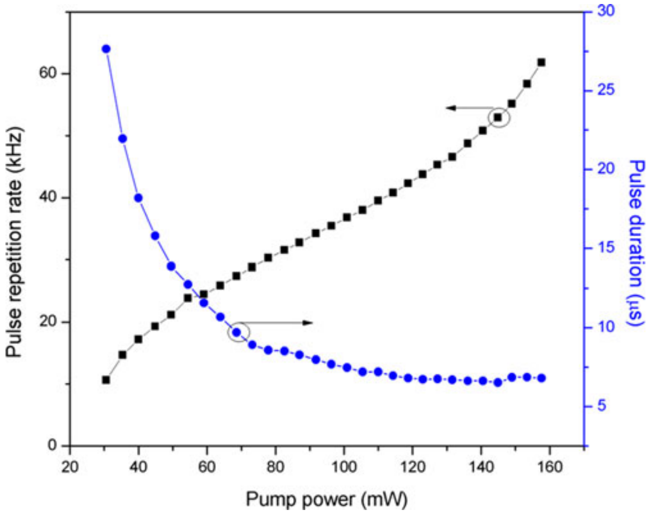


Fig. 4. The Q-switched pulse repetition rate and pulse duration behavior as a function of the optical pump power, with variations from 10.64 kHz to 61.8 kHz and 27.65 μs to 6.8 μs respectively.

depicted in the Fig. 7(b). The output power stability was observed that presents a maximum deviation of ±0.371 dB, ±0.374 dB, and ±0.376 dB for the three different lasing lines [see Fig. 7(c)].

4. Discussion

From Fig. 2(c), it can be observed that the free-running, Q-switched multi-wavelength lasing tends to be broaden with some ripples [see Fig. 2(d)] due to the self-phase modulation [38]. This spectral broadening induces intense mode competition in the laser cavity carrying out instabilities (unstable lasing wavelength and unstable output power). To overcome these instabilities, the insertion of the tapered comb-filter is proposed to reshape the gain spectrum via wavelength-dependent loss and generate stable multi-wavelength laser oscillation (see Fig. 3). The maximum power deviation is ±0.376 dB for the lasing wavelength at 1533.48 nm, corroborating in this way the effectiveness of

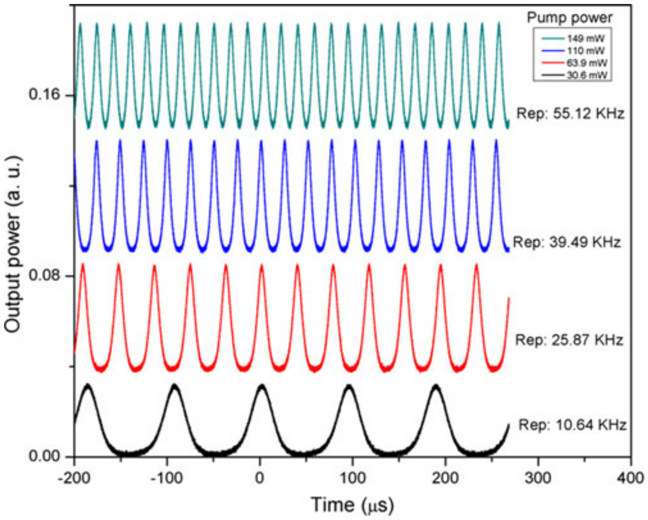


Fig. 5. Four different optical train pulses, showing different repetition rates at 10.64 kHz, 25.87 kHz, 39.49 kHz and 55.12 kHz for the pump powers of 30.6 mW, 63.9 mW, 110 mW and 149 mW.

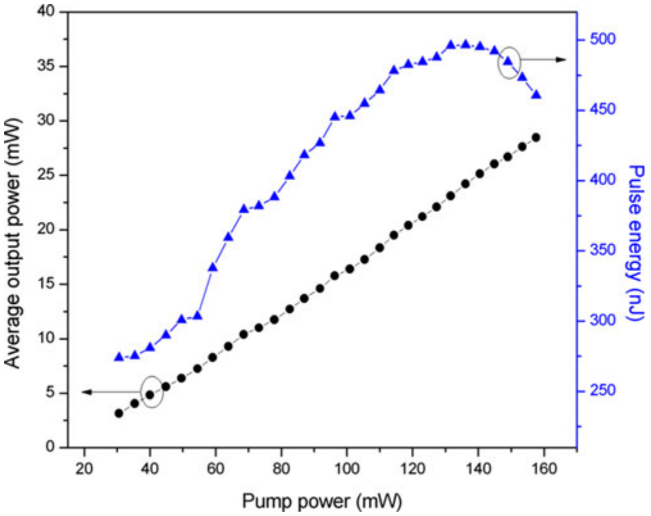


Fig. 6. The performance of the average output power laser and the optical pulse energy as a function of the increment in the pump power.

the comb filter to improve the multi-wavelength emission by mitigating the mode competition and enabling high stability. Just for comparison in the temporal regime, we plotted the repetition rate and pulse duration of the train of Q-switched pulses with and without the filter (Figs. 2(b) and 4). The time pulse duration is about 2 μs slight longer with the filter, due to the elongation of the ring cavity. On the other hand, the fact that only three wavelengths with strong enough intensity are simultaneously lasing generates an increment in the repetition rate range in an order of 4 KHz, because of the faster saturation of the Tm-Ho FSA.

Finally, to compare this proposal with some others that uses different materials and optical effects to stabilize a Q-switched EDFLs, some remarks are given: one advantage of using the Tm-Ho fiber SA and the assisting comb filter is very straightforward, the simplicity of the insertion into the cavity (by fusion splice), while the achieved results are comparable in terms of repetition rates, pulse widths, pulse energy, or output powers with the different SA materials [2], [9], [18]. Besides, the

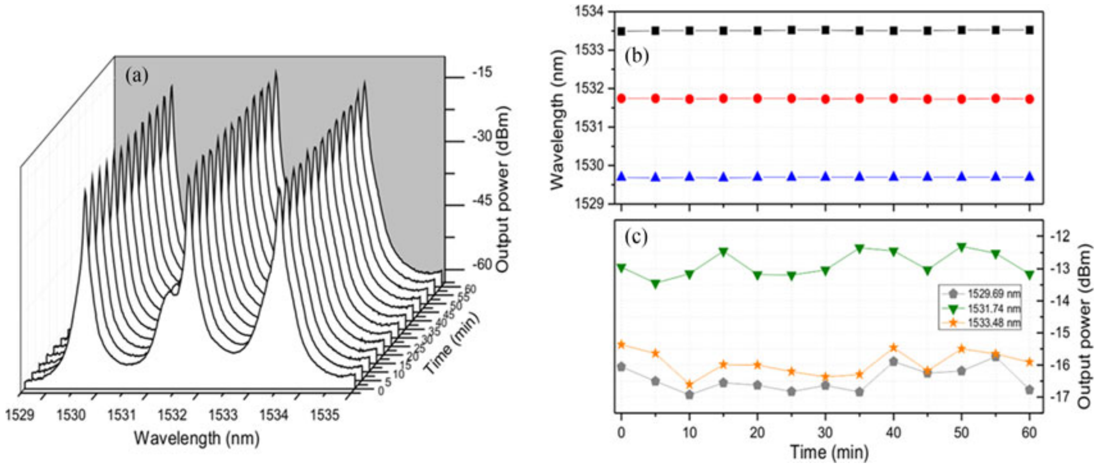


Fig. 7. (a) Spectral distribution of the three lasing wavelengths, taken in samples every 5 minutes within an interval of one hour, (b) the maximum wavelength deviation over time: 0.03 nm, (c) output power deviation of ±0.371 dB, ±0.374 dB, and ±0.376 dB for the respective lasing wavelengths.

tapered comb fiber filter is a relative low-cost simple structure fabricated in standard SMF. Despite the amount of insertion loss, the effect of the proposed filter can be compared to the use of MoS_2 SA acting as a stabilizer of the multi-wavelength lasing emission in the way that suppress effectively the strong mode competition [10]. In the case of the references [36], [37], the Tm-Ho FSA is employed to form the SMS structure to induce mode-beating effect and achieve multi-wavelength lasing emission. In both cases, the FSA needs to have a proper length of Tm-Ho fiber. This requirement may affect directly the dynamics of the Q-switched fiber laser, in terms of pulse width and repetition rates. Also, the sensitivity of the comb filter to the external perturbations such as tension, bending, temperature or changes in the surrounding refractive index can allow the operation of the laser with different features as tunability or switching between the lasing lines, but this issue also could affect the laser stability, so a further study need to be done.

5. Conclusion

In summary, the results of a multi-wavelength Q-switched erbium doped fiber laser, employing 40 cm of Tm-Ho co-doped fiber laser as a FSA were presented. The ring cavity is assisted by a tapered comb fiber filter, allowing high stable triple wavelength emission (1529.69 nm, 1531.74 nm, and 1533.48 nm). Furthermore, stable optical pulses were obtained in the repetition rates from 10.46 kHz to 61.8 kHz with variations in the pulse duration from 27.65 μs to 6.8 μs, an average output power of 27.61 mW and 496.34 nJ for the maximum pulse energy. As far as we know for the first time, the inclusion of the assisted tapered comb-filter promotes the multi-wavelength laser emission of the Q-switched fiber lasers based on Tm-Ho doped fiber as a FSA, besides, act as a stabilizer to improve critical features such as the power and wavelength stability.

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