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Active Q-switched Fiber Lasers with Single and Dual-wavelength Operation

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Additional information is available at the end of the chapter

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Abstract

A brief explanation on Q-switched fiber laser operating principle for active technique in terms of operation characteristics is presented. Experimental analysis of proposed pulsed fiber lasers by the active Q-switched technique is demonstrated. Experimental setups include the use of Er/Yb doped fiber as a gain medium and an acousto-optic modulator as cavity elements. Setup variations include the use of fiber Bragg gratings for wavelength selection and tuning and Sagnac interferometer for wavelength selection in single wavelength operation and for cavity loss adjustment in dual wavelength operation. The experimental analysis of principal characteristics of single-wavelength operation of the fiber laser and cavity loss adjustment method for dual-wavelength laser operation are discussed.

Keywords: Q-switched lasers, Er/Yb double-clad fibers, fiber Bragg gratings, Sagnac interferometer

1. Introduction

Fiber lasers have been studied almost from the onset of laser demonstration. Research on the development of innovative laser systems has been of constant interest in optics and photonics, having fast growth and becoming a central research area in scientific and industrial implementations. Fiber lasers have been widely studied because their unique characteristics of high power confinement, high beam quality, low insertion loss, compactness, and ruggedness. In general, they are attractive for different application areas such as medicine, telecommunications, optical sensing, and industrial material processing.

Fiber lasers make use of stimulated emission to generate light by using an active medium for gain supply. The use of fibers doped with rare-earth elements provides a gain medium with great thermal and optical properties for fiber laser development, in contrast to solid state lasers. Erbium-doped fibers (EDF) have been widely used for fiber laser implementations; however, in the last decade, the constant search of efficiency improvement in terms of very high gain with low pumping thresholds has significantly increased the use of Ytterbium doped fibers because they offer an efficiency above 80% [1].

Moreover, high-power fiber lasers are also of high interest for different applications such as spectroscopy, pump sources, and the study of nonlinear phenomena. In contrast with solid state lasers, a fiber laser requires longer interaction lengths favoring the occurrence of nonlinear effects when high power is achieved, making them desirable for optical switching, nonlinear frequency conversion, solitons, and supercontinuum generation, among other applications.

As it is known, pump diodes provide pump power limited to a few watts. This restriction also limits the fiber laser output power when conventional-doped (single-clad) fibers are used. With the development of double-clad fibers (DCF), high-power fiber lasers experienced significant advances since DCF makes an output power increase attainable. In conjunction with clad-pumping techniques, the DCF feature of large surface area-to-gain volume ratio, in addition to high doping concentration, offer high output power with an improved spatial beam confinement, in contrast with the use of single-clad doped fibers [2].

However, achieving high power continuous-wave (CW) operation of a fiber laser without output power fluctuations is not as straightforward. Taking into account this fact, the development of fiber lasers in pulsed regime provides a feasible alternative. In comparison with CW fiber lasers, pulsed fiber lasers provide high peak power that can be used in the generated wavelength or shifted to other wavelength range by nonlinear frequency conversion.

The most important pulsed regimes are Q-switching and mode-locking. In contrast with CW operation, in pulsed regimes the output is time dependent. In pulsed lasers by the Q-switched technique, stable and regular short pulses are obtained with pulse durations in the nanoseconds range; in contrast to ultrashort pulses obtained by mode-locked techniques, in this case the pulse duration corresponds to several cavity round trips. Q-switching can be developed by passive and active techniques.

Passive Q-switching is performed by using a saturable absorber element placed inside the cavity including graphene [3–5], carbon nanotubes (CNT) [6–8], transition metal-doped crystals [9–11], and semiconductor saturable absorber mirrors (SESAM) [12, 13]. On the other hand, the active Q-switching technique is based on the use of a modulator driven by an external electrical generator. Cavity loss modulation is typically performed by electro-optic modulators (EOM) [14, 15], and acousto-optic modulators (AOM) [16–18]. The EOM and the AOM are based on completely different principles of operation. While the EOM is based on the Pockels effect, the AOM modulates the refractive index of sound waves that generate a periodic grating as it propagates through the medium. In terms of operation, the main difference is the

modulation bandwidth. Typically, the modulation bandwidth of an EOM is 500 kHz to 1 MHz, while for AOM is in the range of 50 to 100 MHz.

The use of the active Q-switching technique for pulsed laser operation allows higher energy pulses and stability. These advantages are increased in lasers based on integrated optics (all-optic) or all-fiber setups.

Otherwise, from the onset of the fiber Bragg gratings (FBG), the incorporation into the design of optical fiber lasers has been almost immediate, contributing significantly to the progress in this particular area. FBGs have been widely used as narrow band reflectors for generated laser wavelength selection. FBGs have unique advantages as optical devices including easy manufacture, fiber compatibility, low cost, and wavelength selection, among others. Moreover, the FBG central wavelength can be displaced or modified by mechanical strain or temperature application [19, 20]. This feature makes them capable devices for fiber lasers wavelength tuning [21] and for all-fiber modulation techniques [22, 23].

Moreover, dual wavelength fiber lasers (DWFL) have been studied previously [24–26]. Obtaining two wavelengths by using a single laser cavity has been attractive for potential application in areas such as optical sources, optical communications, optical instrumentation and others. The phenomenon of obtaining two wavelengths simultaneously with equal powers has been studied in terms of the competition between generated laser lines to improve the stability and DWFL emission control methods.

The use of variable optical attenuators (VOA) and high birefringence fiber loop Sagnac interferometer (*high birefringence fiber optical loop mirror*, Hi-Bi FOLM) have been demonstrated as efficient methods for generating two laser lines simultaneously through the adjustment of losses within the cavity.

Furthermore, wavelength tuning in pulsed DWFL development suggests its possible application in microwave and mainly terahertz generation. For DWFL improvement, different techniques for tuning and setting the separation between generated laser lines have been developed. The main goal in DWFL wavelength tuning is to obtain wide separation and continuous wavelength tuning. A reliable approach for wavelength tuning in DWFLs is the use of FBGs where the Bragg wavelength is shifted by temperature changes [27] or by mechanical strain application [28, 29].

In this chapter, a brief explanation on Q-switched fiber laser operating principle for active technique is presented. Also, a description of operation characteristics of Q-switched lasers, mainly in active Q-switching technique, is presented. Additionally, the current state of the art (to our knowledge) regarding DWFL in actively Q-switched pulsed regime is reviewed.

Furthermore, experimental setups for a dual wavelength actively Q-switched fiber laser and an actively Q-switched fiber laser with single and dual wavelength operations are experimentally demonstrated and analyzed. The experimental results of the lasers are discussed and compared in terms of operation characteristics, including repetition rate, pulse duration, pulse energy, average power, and peak power.

2. Q-Switched fiber lasers: A review from operating principle to single and dual-wavelength operation

Q-switching is a significantly employed technique in fiber lasers improvement. Q-switching is a suitable technique to obtain powerful pulses at low repetition rates from a few kHz to 100 kHz, typically; it can obtain short pulses in nanoseconds range, corresponding to several cavity round trips. This is in contrast with the mode-locking technique in which ultrashort pulses are obtained.

In recent years, Q-switched fiber lasers have been attractive due to their applications in medicine, optical time-domain reflectometry, terahertz generation, optical instrumentation, remote sensing, and materials processing in the industry.

Q-switching is performed by cavity losses modulation. The intracavity losses are maintained on a high level until the gain medium accumulates a considerable amount of energy supplied by the pumping source. Then the losses are abruptly minimized to build up the laser radiation within the cavity. As a result, a pulse with energy in a range of micro-Joules (even milli-Joules) is generated. Thus, the variation of the intracavity losses corresponds to a laser resonator Q-factor modulation. In general, Q-switched fiber lasers can be obtained with continuous or pulsed pump power. In the case of continuous pump power application, an important condition must be considered: a longer gain medium upper-state lifetime is required to avoid energy loss by fluorescence emission to reach stored high energy as a consequence. Particularly, in fiber lasers the saturation energy has to be high to prevent excessive gain that can lead to an early inception of laser generation. The pulse energy is commonly higher than the gain medium saturation energy.

Although Q-switched lasers based on bulk optics are regularly preferred over fiber lasers because of their larger mode areas to store more energy, the incorporation of bulk components in fiber lasers leads to a detriment of simplicity, robustness, and alignment of the laser. Also, the use of bulk elements in fiber lasers produces a beam quality degradation and the addition of high cavity losses, resulting in a decrease of laser performance and efficiency. Thus, in bulk fiber lasers approaches, the use of higher pump powers is required to increase the laser output power [23].

The Q-switching technique can be performed by passive and active methods:

Passive Q-switching is performed by using a saturable absorber element placed inside the cavity, which modulates automatically the losses within the laser cavity. As already mentioned, the variety of saturable absorber elements in passively Q-switched fiber lasers usually includes the use of graphene, CNT, metal-doped crystals, and SESAM [3–13]. The pulse repetition rate is determined and varied by the applied pump power, while the pulse duration and pulse energy are affected by the cavity and the Q-switching element parameters and commonly remain fixed. Thus, the repetition frequency cannot be modified with independence of other operation parameters [30]. To reach an efficient performance, the saturable absorber recovery time, commonly, has to be higher than the pulse duration and lower than the gain medium upper-state lifetime. Laser pulses generated with passive Q-switching typically

present a low repetition rate range because of the applied pump power range. The main advantages of passively Q-switched lasers are their simple designs and low cost due to the fact that the use of external modulators and their electronics are not required.

On the other hand, active Q-switching is based on the Q-factor modulation using a modulator included in the fiber laser design. The modulation element is driven by an external electrical generator. In the active Q-switching technique, the stored energy, when cavity loss is high, generates a pulse soon after an external electrical signal arrives on the modulator driving the intracavity losses to a low level. In this case, the pulse duration and the pulse energy depends on the energy stored by the gain medium. Hence, the pump power and the repetition rate variations modify the achieved pulse duration and pulse energy. For the active technique, the modulating switching time does not have to be similar to the pulse duration, the pulse duration is in any case of the order of the laser resonator round-trip time. As has been mentioned previously, active cavity losses modulation is typically performed by EOMs and AOMs [14–18]. According to the technological progress, the used modulators have been experiencing important changes. In early actively Q-switched lasers approaches, modulators were mainly using bulk components. Then, they were designed by using integrated optics coupled to optical fibers. Recently, all-fiber modulators have been included in fiber laser designs to increase the overall performance of the laser. The acousto-optic Q-switching is performed by a radio frequency (RF) power controlling a transducer. The generated acoustic wave provides a sinusoidal optical modulation of the gain medium density resulting in an intracavity loss modulation. AOMs can rapidly modulate the cavity losses that allows the Q-switched pulses generation with pulse durations of a hundred of nanoseconds. The shortest pulse durations and the highest pulse energies are obtained at the lowest allowed repetition rate, however, at the cost of obtaining low output average power. The use of the active Q-switching technique for pulsed laser operation allows higher energy pulses and stability. These advantages increase with laser designs based on integrated optics or all-fiber laser designs.

Moreover, most of the Q-switched fiber laser approaches are focused on the use of single-clad fibers as a gain medium. In comparison with single-clad Er or Yb doped fibers, Er/Yb double clad co-doped fibers (EYDCF) can be used to suppress the self-pulsing of Er ion-pair [4]. This effect, in addition to cladding pump techniques, can be used to increase the pump power efficiency, minimizing the gain degradation by using EYDCF as a gain medium.

Regarding passively Q-switched fiber lasers, different approaches using EYDCF have been reported [30–33]. Laroche et al. [30] in 2002 presented a pioneer experimental setup of pulsed lasers for passive Q-switched technique using EYDCF as gain medium. They presented an open cavity laser using Cr²⁺:ZnSe as a saturable absorber. V. Philippov et al. [33] reported a similar configuration by using Cr²⁺:ZnSe and Co²⁺:MgAl₂O₄ as saturable absorbers. The maximum average power of 1.4 W was achieved in pulses with durations from 370 to 700 ns for a repetition rate between 20 kHz and 85 kHz.

In the case of actively Q-switched lasers using EYDCF, to our knowledge, a small number of approaches have been reported [34, 35]. Recently, González-García et al. [34] reported a linear cavity EYDCF laser Q-switched by an acousto-optic modulator. The pump power is introduced to the EYDCF by a free space subsystem carefully optimized by using a lenses design.

Nowadays, the development of DWFL has been of interest because of their ability to obtain two laser wavelengths simultaneously by the use of a single cavity. DWFL's advantages are low cost, simple design, fiber compatibility, and low loss insertion devices, making feasible more complex optical devices design. From its first approaches in CW fiber lasers, DWFL research has increased because of their potential applications in different areas such as optical communication systems, optical instrumentation, optical sources, and spectral analysis.

In recent years, the experience in the study of DWFL in CW regime has been incorporated into the implementation of DWFLs in pulsed regime. With this advancement, it has opened the possibility of new applications where high output power is required such as research of nonlinear phenomenon study and remote sensing. The main issue in DWFL operation is centered on the difficulty of obtaining two stable wavelengths simultaneously because doped fibers behave as a homogeneous gain medium at room temperature, causing a competition between the generated laser lines that leads to a generated laser line's instability.

Commonly used methods to balance the generated wavelengths include the use of polarization controllers (PC) and variable optical attenuators (VOA), among others; however, most of them are arbitrary methods in the absence of a measurable physical variable for wavelength competition analysis and characterization, affecting the repeatability in the laser performance. The methods are focused on adjusting laser intracavity losses to balance the simultaneously generated wavelengths. In previously reported investigations, the Sagnac interferometer with high birefringence (Hi-Bi) fiber loop capability has been theoretically and experimentally demonstrated as a trustworthy alternative for the adjustment of losses within the cavity [21, 36–38], since the Hi-Bi FOLM periodical spectrum can be finely displaced in wavelength by temperature variations applied on the Hi-Bi fiber loop [37].

Different experimental setups of DWFL by passive Q-switching technique have been reported [39–41]. However, to our knowledge, there have not been reported approaches using EYDCF as a gain medium. Concerning cavity losses adjustment for dual wavelength laser operation, the most frequent method is the use of PC in ring cavity fiber lasers. H. Ahmad et al. [40] reported a ring cavity passive Q-switched DWFL operating at 1557.8 nm and 1559 nm by using PC for dual wavelength generation. A nonlinear optical loop mirror (NOLM) with a dispersion-decreasing taper fiber (DDTF) in the fiber loop is used as a passive Q-switching element.

Regarding actively Q-switched fiber lasers, only few attempts have been reported in which dual wavelength emission is obtained. In 2013, G. Shayeganrad [42] reported a compact linear cavity actively Q-switched DWFL. The Q-switching is performed by an AOM. The gain medium is a c-cut Nd:YVO₄ crystal with a feature of dual-wavelength generation in Q-switched regime without adjustment elements. An undoped YVO₄ crystal is used for stimulated Raman scattering (SRS) effect enhancement. The SRS simultaneous wavelengths at 1066.7 and 1083 nm are shifted at 1178 and 1199.9 nm.

S.-T. Lin et al. [43] reported a selectable dual-wavelength actively Q-switched laser. By using two electro-optic periodically poled Lithium niobate (PPLN) integrated crystals, the output wavelengths between 1063 and 1342 nm are selected with voltage variations on PPLN Bragg modulators (EPBM) sections. It is worth mentioning that both cited experimental setups are

designed with bulk optic elements with high pump power application, around 20 W. As has been said above, such designs require fine alignment, so typically, efficiency and instability problems are presented.

The all-fiber or optical fiber coupled laser systems promise to be an option for solving alignment issues minimizing losses within the laser cavity. Pump-to-signal efficiency can be increased and, consequently, highly increased pump power is not required to obtain more energetic pulses. However, for such designs, the output power is typically limited by the maximum signal power handled by the employed components.

Therefore, the use of double-clad doped fibers provides a stable and straightforward method to generate high energy nanosecond pulses in actively Q-switched dual-wavelength fiber lasers. From reported investigations, EYDCF offers high conversion efficiency for high-energy pulses generation [44, 45].

Regarding EYDCF use, in 2014, an actively Q-switched wavelength tunable DWFL using EYDCF as a gain medium has been reported [44]. The linear cavity laser incorporates the use of bulk components to introduce pump power in the EYDCF. The laser wavelengths are generated and simultaneously tuned by using a polarization maintaining fiber Bragg grating (PM-FBG). The maximal separation between generated wavelengths of 0.4 nm is adjusted by polarization axis adjustment performed by a PC. The simultaneous wavelength tuning range of ~11.8 nm is obtained by axial strain applied on the PM-FBG. The maximal average power of 22 mW is obtained with a repetition rate of 120 kHz with a pump power of 1.5 W.

Recently, a self-Q-switched (SQS) EYDCF laser with tunable single operation and dual wavelength operation using a Hi-Bi FOLM as a spectral filter was experimentally demonstrated [45]. The wavelength tuning in single wavelength operation and the cavity loss adjustment for dual wavelength operation is performed by temperature variations applied in the FOLM Hi-Bi fiber loop, allowing Hi-Bi FOLM spectrum wavelength shifting. Stable SQS pulses with duration of 4.1 μ J and repetition rate of 25 kHz are obtained with a pump power of 575 mW. The single wavelength tuning range over 8.4 nm is obtained with FOLM Hi-Bi fiber loop temperature variation in a range of ~7.2 °C. Separation between generated simultaneous dual wavelengths is 10.3 nm.

Then, we propose the use EYDCF fiber as gain medium for the design of actively Q-switched lasers with operation in single and dual wavelength. Also, we propose the use of FBGs and Hi-Bi FOLM as cavity elements that allow modifying the characteristics of laser operation and improve its performance by straightforward methods.

3. Actively Q-switched dual-wavelength fiber laser based on fiber Bragg gratings

In this section, an experimental analysis of a ring cavity dual-wavelength actively Q-switched fiber laser with an EYDCF as a gain medium is presented. A pair of FBGs is used for separately generated laser lines tuning by mechanical compression/stretch applied on the FBGs. Simul-

taneously generated dual-wavelength laser lines tuning are presented with wavelengths separation from 1 nm to the maximal separation of 4 nm (without the need of cavity loss adjustment).

The experimental setup is presented in Figure 1. The fiber ring cavity laser is based on the use of 3 m of EYDCF as a gain medium. The EYDCF is pumped with a laser source at 978 nm through a beam combiner. The pump power of 5 W is limited by the maximal AOM signal power of 1 W. An optical isolator with maximal output power of 5 W is used to ensure unidirectional operation. An optical subsystem formed with a 50/50 optical coupler with output ports connected to FBG1 and FBG2 with central wavelengths at 1543 and 1548 nm respectively, allows dual wavelength emission at FBG reflected wavelengths; it is also used for separate laser wavelength emission monitoring at outputs 1 and 2. The FBGs with approximately 99% of maximum reflectance are placed on mechanical devices for generated laser wavelength tuning by applying axial strain on the gratings. The simultaneously generated laser wavelengths are measured at 90/10 coupler output 3. A fiber-pigtailed AOM driven by a RF signal is placed for active Q-switching pulsed laser operation. The output spectra monitored at output ports (1, 2, and 3) are measured with an OSA and also the Q-switched pulses are detected and observed with a photodetector and an oscilloscope, respectively.

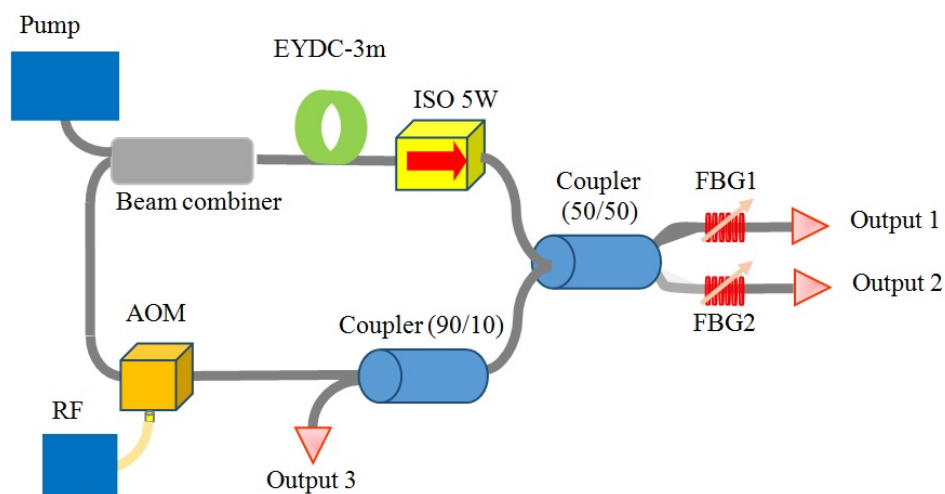


Figure 1. Experimental setup for actively Q-switched dual wavelength ring cavity fiber laser.

Figure 2 shows the experimental results for the dual-wavelength fiber laser spectrum measurements with fixed pump power of 5 W. The measurements were obtained at output 3 with an OSA with attenuation. Output power results are presented in linear scale to support the achieving of two simultaneous laser wavelengths with equal powers. Two simultaneous wavelengths are obtained without requiring cavity losses adjustment in the presented wavelength separation tuning range, however, we noticed the requirement of cavity losses adjustment for wavelength separations above 4 nm. Results for dual wavelength operation with cavity losses adjustment (wavelengths separation above 4 nm) are not presented since it was performed introducing curvature losses by fiber bending applied between 50/50 output

ports and FBGs connections; an arbitrary method in which it is not possible to characterize the competition between the generated laser lines.

Figure 2(a) shows the generated laser lines spectrum measurements for dual wavelength Q-switched laser operation with different wavelength separations. The separation tuning from 1 to 4 nm is achieved by mechanical compression/stretch applied on the FBGs. The repetition rate remained fixed at 70 kHz. As it is shown, dual wavelength laser operation is generated simultaneously with approximately equal laser lines output powers without an adjustment of losses within the cavity. As it can be seen, for the repetition rate and pump power settings, a preference exists to generate the longer wavelength during the competition between the laser lines.

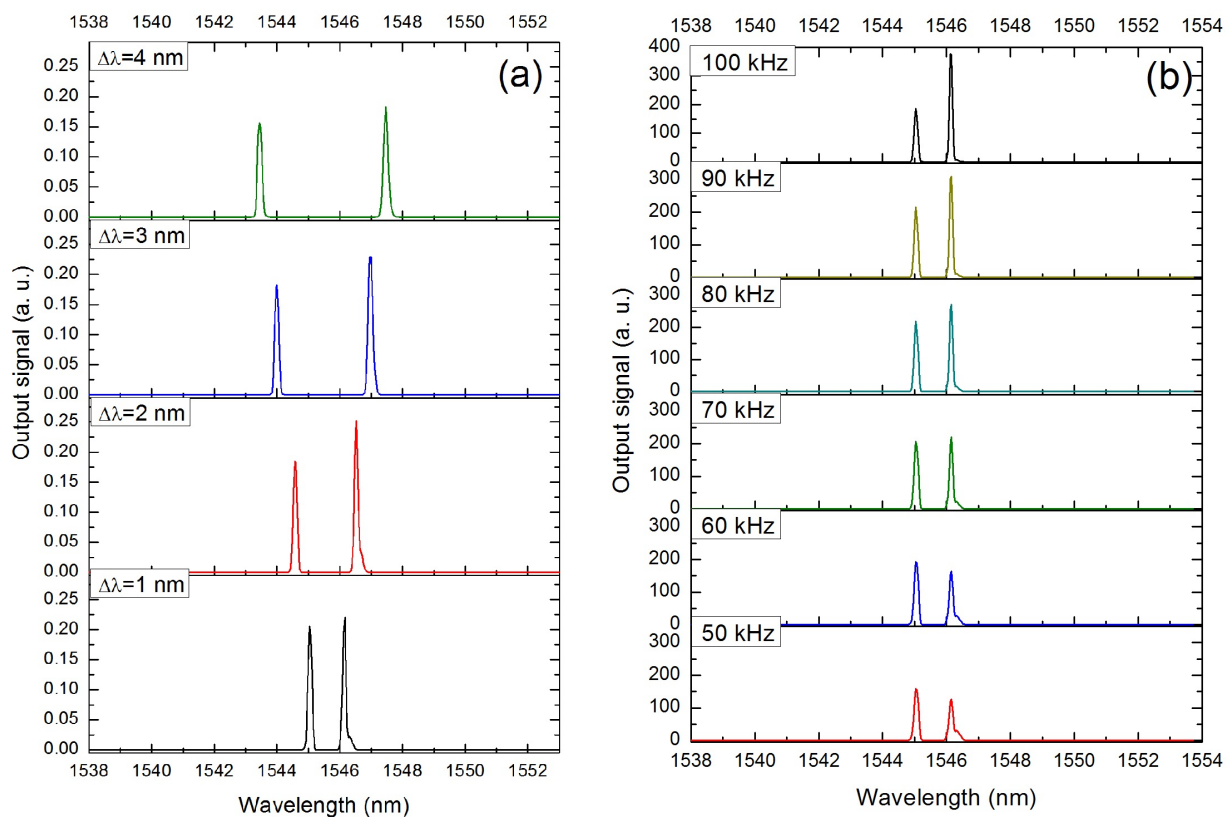


Figure 2. Spectrum measurements for dual-wavelength actively Q-switched laser operation, (a) different generated wavelengths separation tuning with fixed repetition rate, (b) generated laser lines with wavelength separation of 1 nm and repetition rate variations.

Figure 2(b) shows the generated dual wavelength laser lines with fixed wavelength separation of 1 nm ($\lambda_1 = 1545.2$ nm and $\lambda_2 = 1546.2$ nm) for repetition rate variations from 50 to 100 kHz. As it can be observed, output powers for both simultaneous wavelengths increase when the repetition rate is increased. The competition between generated laser lines presents a preference to generate the longer wavelength as the repetition rate is increased, however, dual wavelength laser operation is presented over the repetition rate range without cavity losses adjustment.

Figure 3 shows the output power ratio for the two simultaneously generated laser lines measured $P(\lambda_2)/P(\lambda_1)$, where λ_1 and λ_2 are the shorter and the longer laser wavelengths, respectively. The spectrum measurements were performed at output 3 with an OSA and output powers were individually monitored at output 1 and 2 with a photodetector and a power meter. The measurement of the power ratio between generated laser lines is a straightforward method for numerically analyzing the competition between laser line behavior. With output power ratio $0 < P(\lambda_2)/P(\lambda_1) < 1$, the shorter wavelength is generated with power above the longer wavelength. On the other hand, for $P(\lambda_2)/P(\lambda_1) > 1$, the longer wavelength presents an output power above the shorter wavelength. As it has been previously shown for the proposed experimental setup, there exists a preference to generate the longer wavelength. Furthermore, it was shown that the Q-switched dual wavelength fiber laser output powers are modified with repetition rate and tuned wavelength variations.

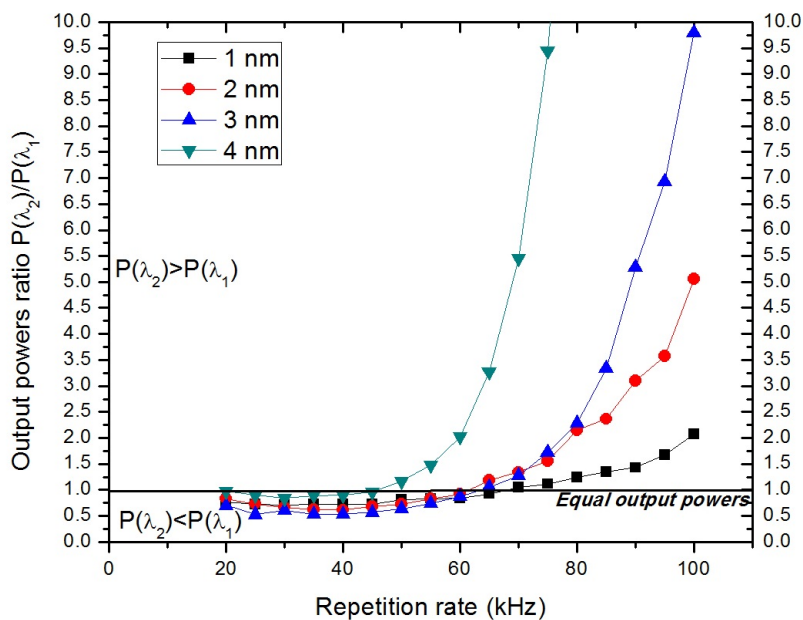


Figure 3. Dual wavelength operation generated laser wavelengths power ratio $P(\lambda_2)/P(\lambda_1)$ for repetition rate variations and different wavelengths separations.

In Figure 3, it can be clearly observed that with increasing repetition rate, the competition between laser lines has an imbalance in which the longest wavelength has a preference to be generated. Strong competition allowing dual wavelength laser operation with almost equal output powers from 20 kHz to about 60 kHz of repetition rate can be observed. With repetition rate variations from 60 kHz to 100 kHz, the longer wavelength output power increases significantly, at the expense of the shorter wavelength output power. As it can be also observed, the range of repetition values over which the longer wavelength starts growing significantly is shortened when increasing the separation between the generated laser wavelengths. As it is shown, for a wavelength separation of 1 nm, the maximum power ratio is about 2 times, with a repetition rate of 100 kHz. However, for a wavelength separation of 4 nm and a repetition rate of 70 kHz, an output powers ratio in which λ_2 is 9.5 times greater than λ_1 is observed.

Figure 4 is a group of experimental results for actively Q-switched dual wavelength laser pulses. The results also show pulse profiles for different repetition rate variations, comparison between pulses measured at different outputs, and experimental analysis of pulses time shift by repetition rate variations.

Figure 4(a) shows the optical pulse measurements for actively Q-switched dual wavelength laser operation. The wavelength separation remains fixed at 4 nm between simultaneously generated laser lines. With the use of a photodetector and an oscilloscope, the pulse traces together with the leading pulse of the signal applied to the AOM were obtained at output 3 where both generated wavelengths are simultaneously measured. The resulting pulses were obtained for different repetition rate variations from 50 to 100 kHz. For actively Q-switched operation, with the increase of repetition rate, the pulse duration typically increases as pulse amplitude decreases. As it can be seen, with a repetition rate of 50 kHz, there is a time shift of 93.7 ns between the leading edge of the electrical pulse applied to the AOM and the generated laser pulse. As we can observe, the time shift depends on the repetition rate.

The dependence of the temporal pulse shift on the repetition rate variations is shown in Figure 4(b). As it is shown, the pulse time shift increases as the repetition rate increases. Thus, it can be observed that for a repetition of 100 kHz, the pulse temporal shift between the electrical modulation signal leading edge and the generated pulse increase to $\sim 2.3 \mu\text{s}$.

Figure 4(c) shows the pulse traces that correspond to the same dual wavelength generation with wavelength separation of 4 nm and repetition rate of 50 kHz. Since the FBGs have a reflection close to 100% at the central wavelength, it is possible to obtain independently single laser concerning each of the generated laser wavelengths at the outputs 1 and 2 as a result of the signal transmitted by each FBG. Thereby, the pulses generated by the laser wavelength $\lambda_1 = 1543.5 \text{ nm}$ (blue line) obtained at output 2 and the optical pulses for wavelength $\lambda_2 = 1547.5 \text{ nm}$ (red line) acquired at output 1 are shown together with the optical pulse for both λ_1 and λ_2 measured at output 3. As it is shown, a slight time shift and pulse widening is observed for both wavelength pulse measurements (output 3) compared to the individual pulses observed for λ_1 and λ_2 .

Figure 5 shows the output power in dual wavelength operation for generated laser wavelength separations $\Delta\lambda = 1 \text{ nm}$ ($\lambda_1 = 1545.2 \text{ nm}$ and $\lambda_2 = 1546.2 \text{ nm}$) and separation $\Delta\lambda = 4 \text{ nm}$ ($\lambda_1 = 1543.5 \text{ nm}$ and $\lambda_2 = 1547.5 \text{ nm}$) as a function of the repetition rate variations over the range from 30 kHz to 100 kHz, with the used pump power of 5 W. The difference between measured average power for both wavelength separations $P(\Delta\lambda = 1 \text{ nm}) - P(\Delta\lambda = 4 \text{ nm})$ at the same repetition rate for both measurements is also shown. The average power was measured at output 3 with a power meter. As what typically occurs in actively Q-switched fiber lasers, it is observed that the average power increases with the repetition rate increase. As can be seen, the maximal average power is obtained with repetition rate of 100 kHz. For the dual wavelength operation with laser lines separation of 1 nm the maximal average power (red line, squared symbol) is 496 mW while it is 490 mW for a separation of 4 nm (blue line, circled symbol). The difference between average power measured for both wavelength separations tuned in a range from -10 mW to 10 mW is observed. As it can be also observed, the behavior

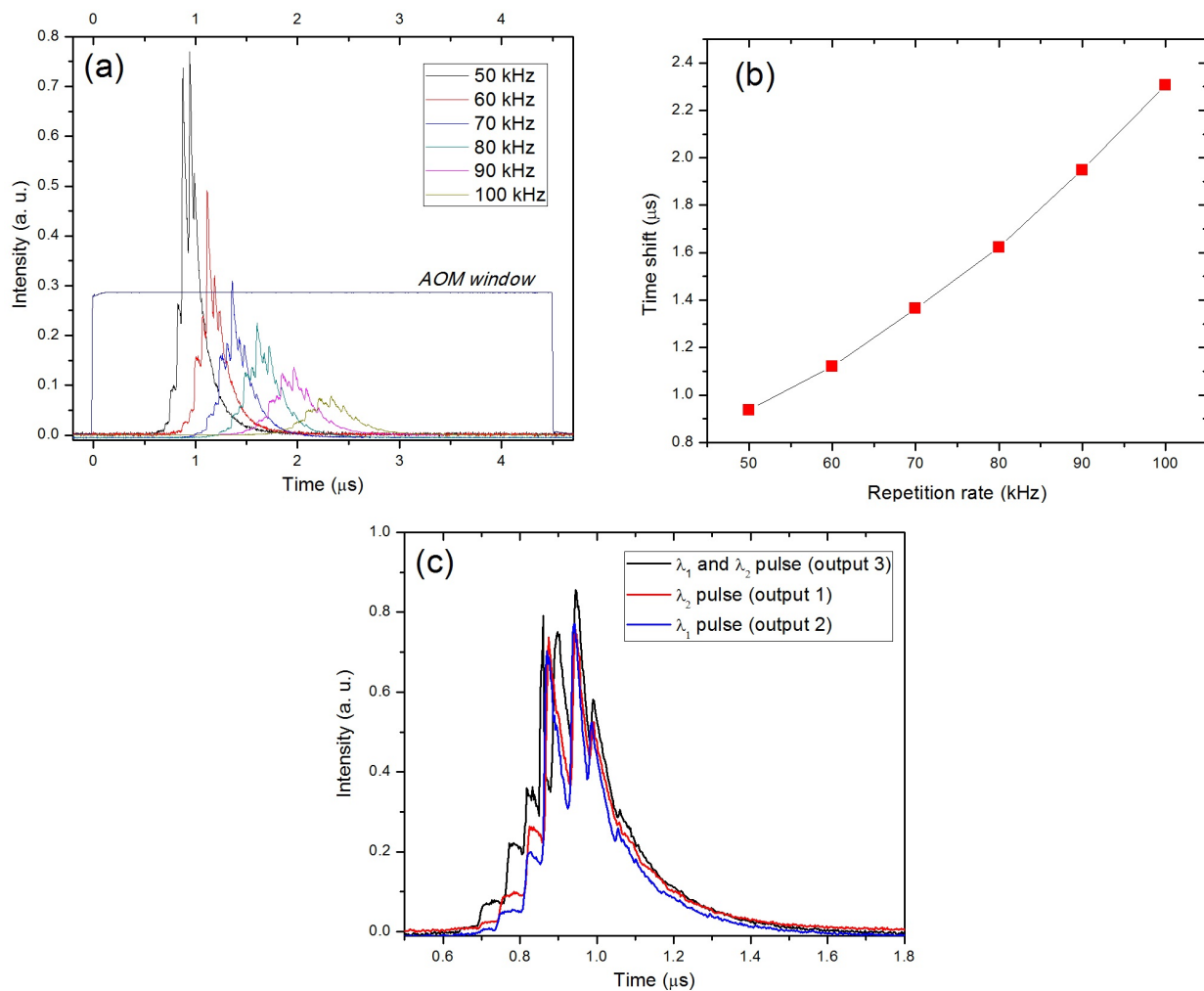


Figure 4. Optical pulses for Q-switched dual-wavelength operation with wavelength separation of 4 nm, (a) pulse profiles with repetition rate variations, (b) pulse time shifts on repetition rate variations, (c) separate pulse profiles for λ_1 and λ_2 , and both λ_1 and λ_2 pulses with repetition rate of 50 kHz.

of average power on repetition rate has no significant variations with respect to the tuned wavelength separation between generated laser lines.

Figure 6 shows the measured pulse duration and the estimated pulse energy on repetition rate variations and the estimated pulse peak power for dual-wavelength laser operation. Results are obtained for wavelength separation between generated laser lines of 1 nm and 4 nm. Pulse profiles for Q-switched dual wavelength operation with both generated wavelength separations were performed with a photodetector and monitored by an oscilloscope. From pulse shape measurements, pulse duration was obtained. The pulse energy for each wavelength separations is estimated with the repetition rate and the average power results shown in Figure 5. Estimation of pulse peak power is obtained with the pulse energy and the pulse duration achieved results.

Typically for actively Q-switched lasers, with the increase of repetition rate, the obtained pulses widens increasing the pulse duration. Thus, although the pulses train average power

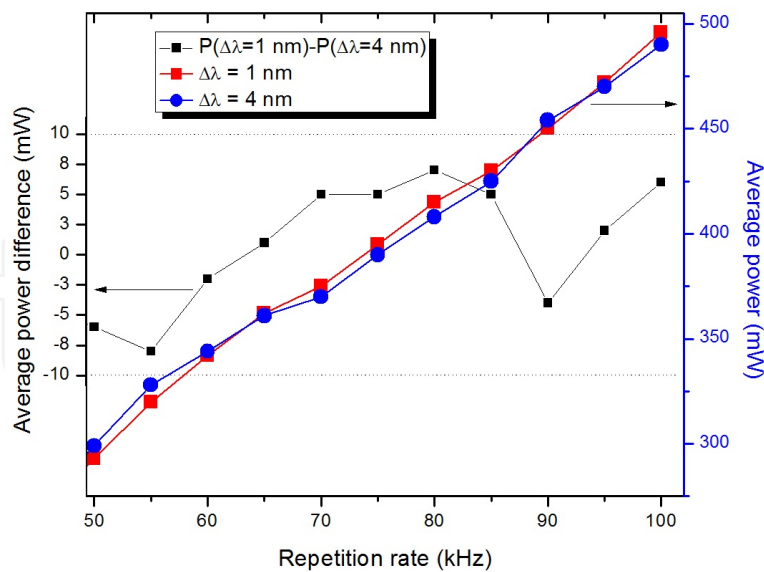


Figure 5. Average power on repetition rate variations of Q-switched dual wavelength operation with wavelength separations of 1 nm and 4 nm.

increases with the repetition rate increase (see Figure 5), the optical pulses are less energetic by the widening and the pulse peak power reduction experienced (see Figure 4(a)).

Figure 6(a) shows the pulse duration and pulse energy on repetition rate variations for dual wavelength laser operation. The pulse duration and pulse energy show a typical behavior of actively Q-switched lasers. With the repetition rate increase, pulse duration increases and pulse energy decreases are observed. For simultaneously generated laser wavelength separation of 1 nm, maximal pulse energy (blue line, circled symbol) of $\sim 5.86 \mu\text{J}$ and minimal pulse duration (black line, circled symbol) of $\sim 220 \text{ ns}$ are obtained with the minimal repetition rate of 50 kHz. Similarly, for a wavelength separation of 4 nm at the same repetition rate, the maximal pulse energy (blue line, squared symbol) of $5.98 \mu\text{J}$ and the minimal pulse duration of 295 ns is obtained.

The estimated pulse peak power on repetition rate variations is shown in Figure 6(b). As it can be observed, the pulse peak power (pulse amplitude) for the wavelength separation of 1 nm is higher compared with what is observed for the wavelength separation of 4 nm. This result is essentially attributed to a smaller increase in pulse duration for the measurements of $\Delta\lambda = 1 \text{ nm}$ as the repetition rate is increased (shown in Figure 6(a)). For $\Delta\lambda = 1 \text{ nm}$ and $\Delta\lambda = 4 \text{ nm}$, the maximal pulse peak power of $\sim 26.6 \text{ W}$ and $\sim 20.27 \text{ W}$, respectively, are obtained for the minimal repetition rate of 50 kHz, when the pulse widening is minimal.

In this section, an experimental analysis of an actively Q-switched ring cavity fiber laser has been presented. Through experimental and estimated results of laser spectra emission and generated laser pulses, the behavior of the dual wavelength laser operation of competitions between the simultaneously generated laser lines and the evolution of generated laser pulses has been analyzed. Actively Q-switched pulsed laser parameters as repetition rate, pulse duration, pulse energy, average power of the laser emission, and peak pulse power has been

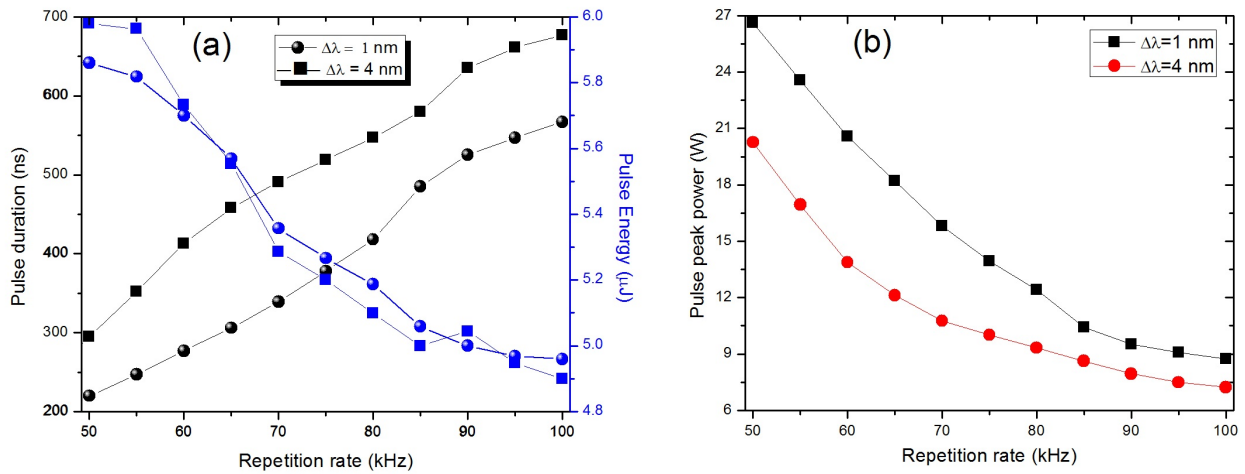


Figure 6. Q-switched dual wavelength operation with wavelength separations of 1 nm and 4 nm on repetition rate variations, (a) pulse duration and pulse energy, (b) pulses peak power.

also experimentally studied in terms of different tuned separations for two simultaneously generated wavelengths and variations on rate repetition of the electrical signal applied to the AOM. Results have been shown that are generalized to any actively Q-switched laser and particularly for lasers with dual wavelength operation. It is worth mentioning that for the proposed experimental setup, it is not necessary to implement a cavity losses adjustment method for the shown operation tuning range (wavelengths separations from 1 to 4 nm), however, a cavity losses adjusting method is required when during the competition between generated laser wavelengths there exists a wavelength preferred for the laser emission.

4. Actively Q-switched dual-wavelength fiber laser with a Sagnac interferometer for cavity losses adjustment

In this section, a linear cavity actively Q-switched fiber laser is proposed for experimental analysis. In contrast to the laser experimental setup demonstrated in the previous section (in which explaining the parameters of active Q-switched fiber lasers was intended), the experimental laser setup is a linear cavity configuration in which a method to adjust the losses within the cavity (when required) for simultaneous dual wavelength laser operation is presented. The proposed configuration includes the use of a Sagnac interferometer with high birefringence fiber in the loop (Hi-Bi FOLM) used as a spectral mirror and mainly for cavity loss adjustment during the laser lines competition in two simultaneous laser lines generation. The use of Hi-Bi FOLM as a reliable method of cavity losses adjustment for lasers operating in dual wavelength application has been extensively studied by our research group [21, 37, 38, 45]. The main objective of this section is to illustrate through a proposed experimental setup that the Hi-Bi FOLM can also be used to implement dual wavelength fiber lasers in pulsed regime for the actively Q-switched technique as well as the experimental analysis of dual wavelength laser operating parameters.

The proposed actively Q-switched fiber laser experimental setup is shown in Figure 7. The linear cavity laser is bound by two FBGs at one end and a Hi-Bi FOLM at the other end. A 3-m length of EYDCF used as a gain medium is pumped by a laser source at 978 nm through a beam combiner. The pump power was fixed to 1.5 W. An AOM driven by an RF signal generator is used for application of the active Q-switching technique. FBG1 and FBG2 with reflections of 99% at central wavelength tuned to 1542.7 nm and 1552.7 nm, respectively, are used as narrow band mirrors for generated laser wavelengths selection. With the selected FBGs central wavelengths, the separation between generated laser lines is ~10 nm. The Hi-Bi FOLM is formed by a 50/50 coupler with output ports interconnected through a Hi-Bi fiber segment of ~56 cm. The Hi-Bi FOLM is acting as a wide band mirror with a periodical spectrum. With the selected Hi-Bi fiber segment, the spectrum period is ~10.3 nm [35]. The Peltier device used for Hi-Bi fiber temperature control is used to shift the Hi-Bi FOLM spectrum in wavelength. This Hi-Bi FOLM spectrum displacement is the method for cavity losses adjustment for dual wavelength laser operation [35]. The splices between Hi-Bi fiber ends and 50/50 output ports are placed in mechanical rotation stages for Hi-Bi FOLM transmission spectrum amplitude adjustment [35]. The Hi-Bi FOLM amplitude was adjusted near maximal contrast. The unconnected 50/50 coupler port (output port) is used for Hi-Bi FOLM transmission spectrum measurement (with pump power below the laser generation threshold) and for laser spectrum measurement with an OSA. The output port is also used for pulses detection by a photodetector and observed on an oscilloscope.

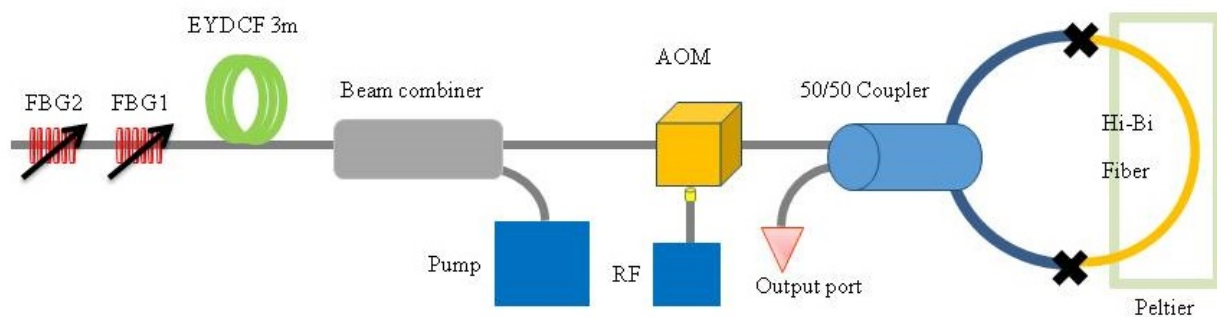


Figure 7. Experimental setup for actively Q-switched linear cavity dual wavelength fiber laser.

Figure 8 shows the cavity losses adjustment performance for single and dual wavelength laser operations. The adjustment is performed by temperature changes in the Hi-Bi FOLM fiber loop. The temperature meter and control has a resolution of 0.06 °C. The repetition rate was set to 60 kHz.

Figure 8(a) shows the three Hi-Bi FOLM transmission spectrum for the Hi-Bi fiber loop temperatures in which single wavelength operations for λ_1 and λ_2 and dual wavelength operation is generated. The Hi-Bi FOLM spectrum measurements were performed with pump power below the laser generation threshold at the output port with an OSA. As it can be seen, dual wavelength laser operation is obtained with Hi-Bi fiber loop temperature of 25.9 °C in which cavity losses are balanced. With the Hi-Bi loop temperature increase, the spectrum shifts to shorter wavelengths performing an imbalance in the competition between the laser lines, thus, the shorter wavelength ($\lambda_1 = 1547.2$ nm) laser emission is favored. On the other hand, a

decrease in Hi-Bi FOLM loop temperature favors the emission of the longer wavelength ($\lambda_2 = 1547.2$ nm). In Figure 8(b), the laser spectrum emission for dual wavelength operation and single wavelength operations for λ_1 and λ_2 are shown. The measurements were performed with pump power of 1.5 W. As it is shown, single wavelength laser operation for λ_1 and λ_2 are obtained with temperatures of 26.6 °C and 25.1 °C, respectively. Dual wavelength operation with approximately equal powers is obtained with Hi-Bi fiber loop temperature of 25.9 °C. The temperature operation range is ~ 1.5 °C.

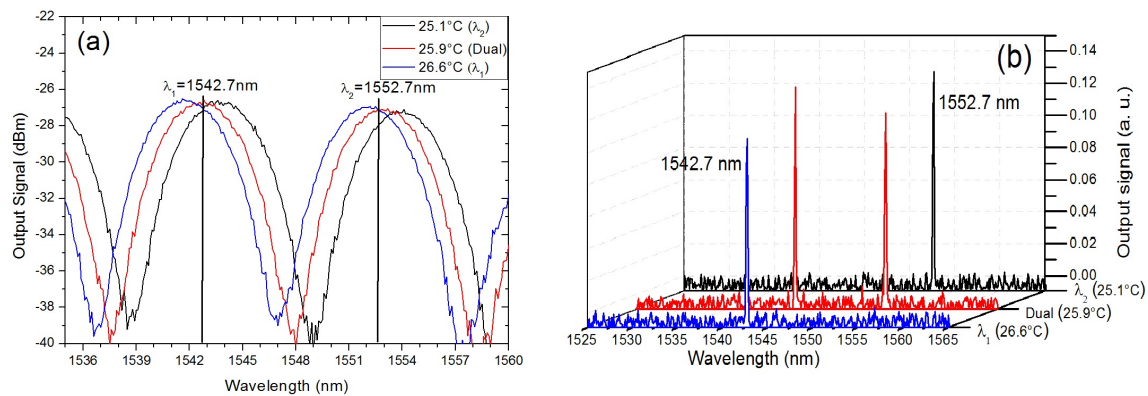


Figure 8. Cavity losses adjustment for laser operation, (a) Hi-Bi FOLM transmission spectrum wavelength displacement for single and dual wavelength operation Hi-Bi fiber temperatures, (b) generated laser spectra for single and dual wavelength operations.

In Figure 9, pulsed regime measurements for actively Q-switched dual wavelength laser operation are presented. Pulse train profile and average power on repetition rate variations are shown.

Figure 9(a) shows the pulse train in time domain for dual wavelength laser operation with repetition rate of 60 kHz measured at the output port. The Hi-Bi fiber loop temperature was set to 25.9 °C for dual wavelength operation with equal powers as it is shown in Figure 8(b). For repetition rates below 35 kHz and above 75 kHz, unstable pulses are generated since the laser pulses displace out of the modulating AOM electrical signal time window. The inset on Figure 9(a) shows a sample pulse from the pulses train. The estimated pulse duration is ~ 448 ns.

In Figure 9(b), the average power on repetition rate variations for dual wavelength operation is shown. Measurements obtained with pump power of 1.5 W and repetition rate from 35 to 75 kHz, were performed at the output port with a power meter. As it can be seen, the average output power increases with the repetition rate from 58.3 to 84.9 mW.

Figure 10 shows the experimental results of pulse parameters for the actively Q-switched laser on dual wavelength operation. Measured pulse duration and estimated pulse energy and pulse peak power dependences on repetition rate variations are shown.

In Figure 10(a), results for pulse duration and pulse energy on repetition rate variations from 35 to 75 kHz are presented. As it can be observed, pulse duration and pulse energy present a behavior typically obtained in actively Q-switched lasers. Pulse duration increases as pulse

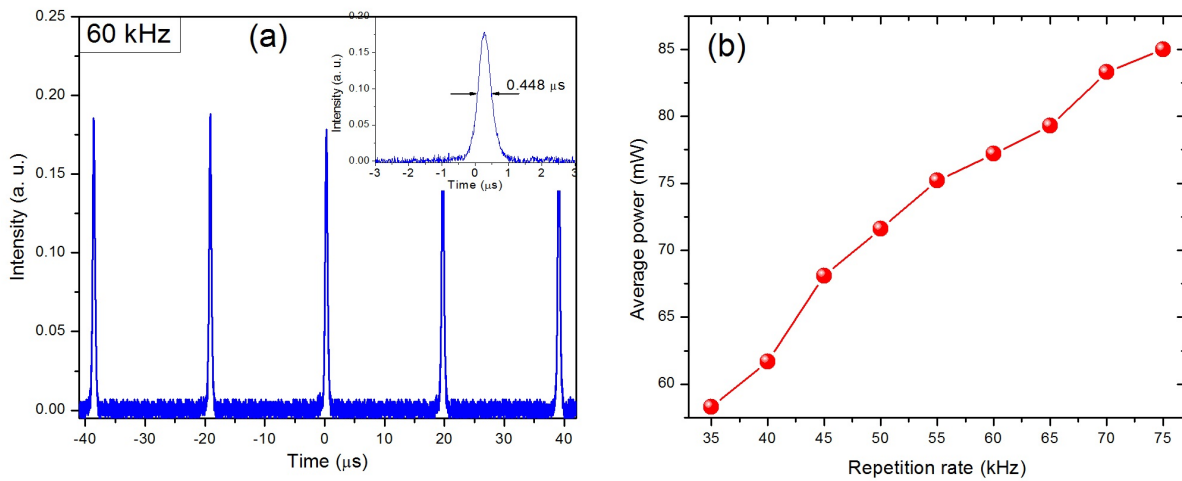


Figure 9. Actively Q-switched dual wavelength laser operation measurements, (a) pulse train with repetition rate of 60 kHz, (b) average power on repetition rate variations.

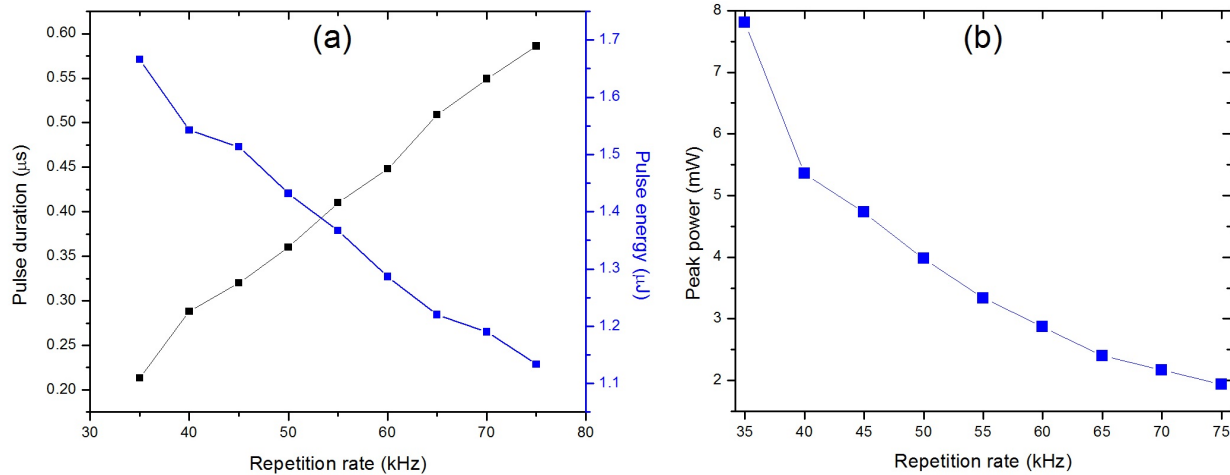


Figure 10. Actively Q-switched dual wavelength laser operation pulse parameters, (a) pulse duration and pulse energy on repetition rate variations, (b) pulse peak power on repetition rate variations.

energy decreases with the repetition rate increase. The pulse duration shows a widening in a range of 213 to 586 ns. The pulse energy decreases as the pulse widens from 1.67 to 1.13 μJ.

Figure 10(b) shows the pulse peak power dependence on repetition rate variations. As it is shown, the pulses undergo a peak power decrease as repetition rate increases. With the lower repetition rate, the pulses have less pulse duration, are more energetic, and with a higher peak power.

5. Conclusions

In this chapter, actively Q-switched fiber lasers for single and dual wavelength operation have been experimentally investigated. The investigation is based on single and dual wavelength

operation of actively Q-switched fiber lasers. The documental investigation is focused on reported approaches on Q-switched fiber lasers taking into account cavity elements, configurations, experimental results, and new fiber technologies incorporation.

A review from the operating principle of pulsed lasers in the Q-switched technique to single and dual wavelength operation, mainly those lasers that use an active Q-switching method was presented. The research was led to reach the point where double clad fibers (specifically EYDCF) are used as the gain medium and the application of the active Q-switching technique by using AOM.

An analysis of the main parameters of actively Q-switched fiber lasers, including the repetition rate, pulse duration, pulse energy, average power, and peak power characteristics of the technique was experimentally discussed. This experimental study was presented in terms of a couple of proposed actively Q-switched fiber laser experimental setups.

The actively Q-switched parameters' typical behavior was mainly discussed in the first experimental setup proposed, a ring cavity dual wavelength actively Q-switched fiber laser based on the use of fiber Bragg gratings for wavelengths selection. The second experimental setup is a linear cavity actively Q-switched fiber laser with single and dual wavelength operations with a Hi-Bi FOLM. The use of the Hi-Bi FOLM as a method to adjust the losses within the cavity (when required) for simultaneous dual wavelength laser operation was discussed.

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