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Compact wavelength-tunable actively Q-switched fiber laser in CW and pulsed operation based on a fiber Bragg grating

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Abstract

We report a double-clad Er/Yb doped fiber tunable laser in continuous wave (CW) and actively Q-switched modes using a fiber Bragg grating (FBG) as wavelength selective in a linear cavity resonator. The laser was tuned in a range from 1532 to 1542 nm for both CW and pulsed modes. The minimum pulse duration was 420 ns at a repetition rate of 120 kHz and ~0.7 W average output power in CW (slope efficiency of ~8%) and 1.03 W average output power in pulse mode (slope efficiency of ~12%).

Keywords: erbium-doped fiber, fiber Bragg grating, actively Q-switched

(Some figures may appear in colour only in the online journal)

1. Introduction

Light pulse sources in the eye-safe wavelength region near 1550 nm have many potential applications in laser machining, free-space communication, range finding, nonlinear frequency conversion and medical surgery. They are compact, robust and require virtually no maintenance, because of their excellent beam quality, high brightness, outstanding efficiency, driver selection, compactness and because they are readily compatible with optical fiber systems [1–3]. With the adoption of double-clad fibers and clad-pumping techniques [4–6], output pulses with peak powers from hundreds of watts to more than 1 kW [6–8] and pulse energies of multiple millijoules in the pulsed mode can be obtained for applications where short pulses are required [9–12]. Q switching is an effective method to obtain giant short pulses from a laser. In the Q-switching operation, the cavity loss is kept at a high level until the pumped gain medium has stored a certain amount of energy. The cavity loss is then quickly reduced to a small value, which allows the intense stimulated laser radiation to be established quickly in the cavity. A short optical pulse is finally released and its energy can lie in the millijoules to joule range [13]. Q switching can be realized in either an active or passive way [14–16]. The former usually needs an active control element, e.g. either an acousto-optic modulator (AOM), an electro-optic modulator (EOM), or a mechanical element (such as a rotating mirror). Both output pulse energy and pulse duration depend on the cavity loss and the energy stored in the gain medium that is related to the pump power and the repetition rate. The advantage of active Q switching is easy control of the pulse repetition rate and consequently, the pulse width, whereas the disadvantage is the requirement of an optical modulator. A saturable absorber is usually adopted in passively Q-switched schemes. In many cases, the pulse energy

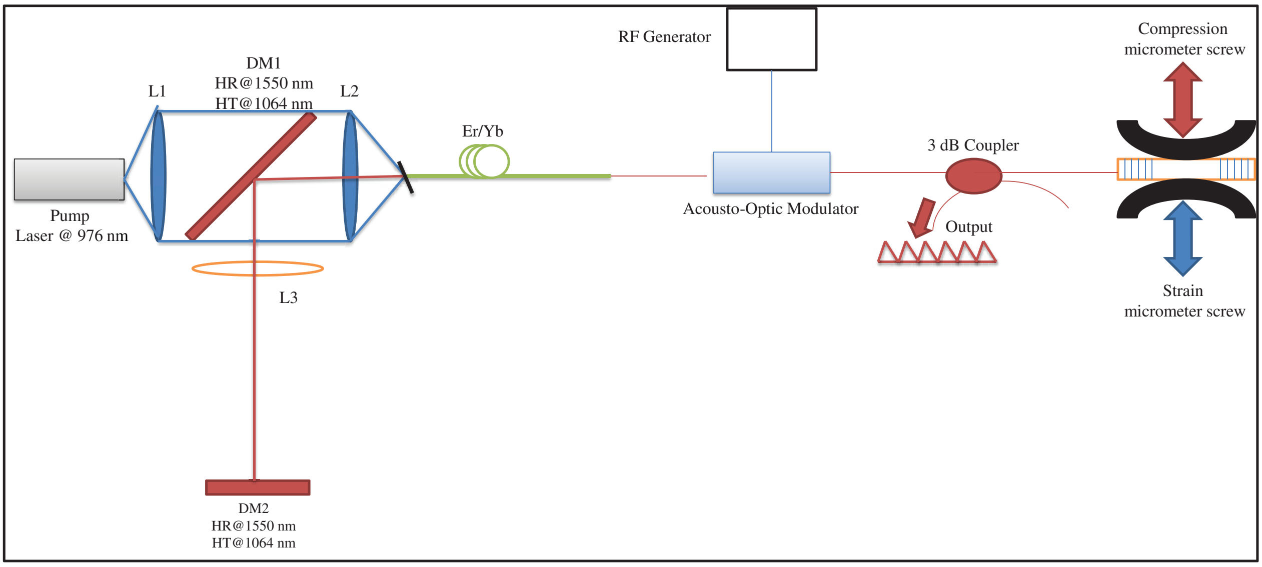

Figure 1. Configuration setup of our Q-switched tunable Er/Yb doped fiber laser.

and duration are rather stable and the pump power can only affect the pulse repetition rate. The major advantage of passive Q-switching is a simpler structure, while the disadvantage is the limitation of the pulse control. In both Q-switched schemes, the pulse duration achieved with Q-switching is typically in the nanoseconds range (corresponding to several cavity round trips). The pulse repetition rate usually lies in the range of hundreds of Hertz to hundreds of kilohertz. Most of the tunable fiber lasers contain a FBG, which are proposed for synchronous tuning of the high reflection in the output of the FBG to obtain an emission in a 1 μm range [17]. Another technique uses a polarization maintaining FBG, to obtain single wavelength emission and dual-wavelength emission near to the C-band of communications [18, 19]. In another technique, emissions are obtained in a range of 2 μm by implementing Ho-doped fiber using a FBG as a reflector [20] and another technique presents a wide range using a novel technique for the multimode interference in the cavity of the fiber laser [21]. All these FBGs were written in the core of an optical fiber by UV light that is present in a resonance reflector with narrow reflection spectrum for the laser.

In this work, we focus on an actively Q-switched rare-earth-doped fiber laser with repetition rates of tens of kilohertz, which has extensive applications in laser machining and laser ranging. Our main motivation for our work is its potential application for tunable sources with mW output power for spectroscopy and THz applications.

2. Configuration setup

The CW and actively tunable Q-switched doped fiber laser setup is depicted in figure 1. The setup includes a high power pump diode laser and a span of 3 m of Er^{3+}/Yb^{3+} double clad doped fiber as gain medium, with a core diameter of 7 μm, an inner cladding diameter of 130 μm and outer cladding diameter of 245 μm. In the configuration setup were included two dichroic mirrors (DM1 and DM2), with high transmission at 1064 nm and high reflectivity at 1550 nm for a 45° and 0°.

The numerical aperture (NA) of the signal is 0.17 and the inner cladding to outer cladding is 0.46. An acousto-optic modulator was inserted in the cavity. The pump light is launched into the cavity through the combination of two optical sub-systems. At the end of the doped fiber was spliced a span of 1 m length of Corning SMF-28 fiber, in order to attenuate the residual pump signal and 1064 nm emission of Yb. At the beginning of the Er/Yb doped fiber we cleave an angle of 8° in order to avoid the 4% of Fresnel refection. The fiber Bragg grating (FBG) has a peak reflectivity ~100% at 1537.8 nm, with a 3 dB bandwidth ~0.5 nm and it was carefully placed on a steel sheet with 2 × 10 cm^2 dimensions and the FBG and steel sheet were placed on a mechanical system in order to apply screwing, compression and lateral stretching in the FBG. The laser cavity was linear and it was formed by the FBG and DM2 for a total cavity length about 8 m. The output average power was measured by a power meter PM100D in the 3 dB coupler. A 10 GHz photodetector IR and a digital oscilloscope with 100 MHz of bandwidth and 1.25 GS s^{-1} were used to measure the pulse shape; an optical spectrum analyzer (OSA) with a minimum resolution of 30 pm, was also used to measure the optical spectrum.

3. Results and discussion

For a first experiment, we operate the laser in CW, for it was removed the AOM where the radiation coming from the doped fiber in the 1550 nm region was sent directly to the FBG through a span of 1 m of a Corning SMF-28 fiber. Applying lateral compression and stretching on the FBG by a micrometric screw, we obtained wavelength tuning in a range from 1532 to 1542 nm, initializing at 1537.8 nm (Bragg wavelength) with a bandwidth of 0.17 nm for each wavelength tuned. Applying compression on the FBG through the micrometric screw, the Bragg wavelength moves to the shorter wavelengths (1537.8

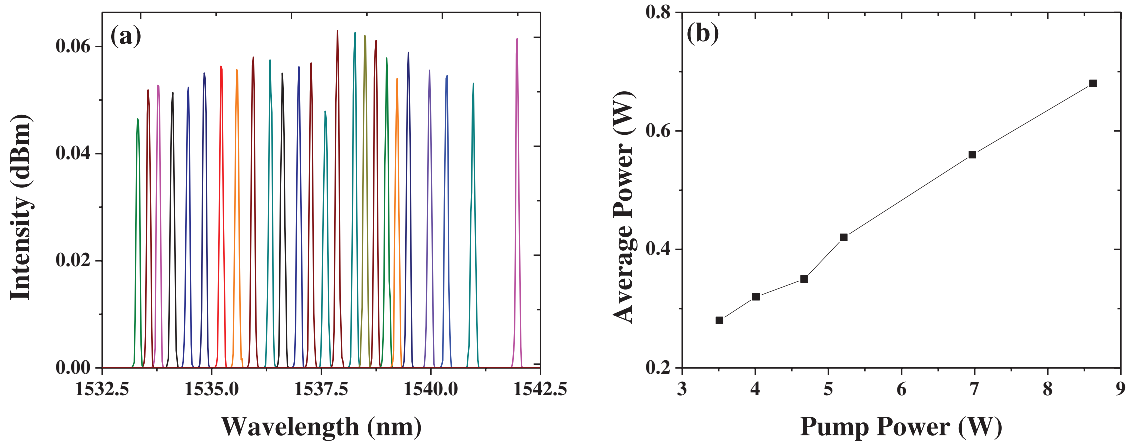

Figure 2. (*a*) Output spectra for the CW tuning wavelength. (*b*) Spectral lasing for the CW laser at 1537.8 nm.

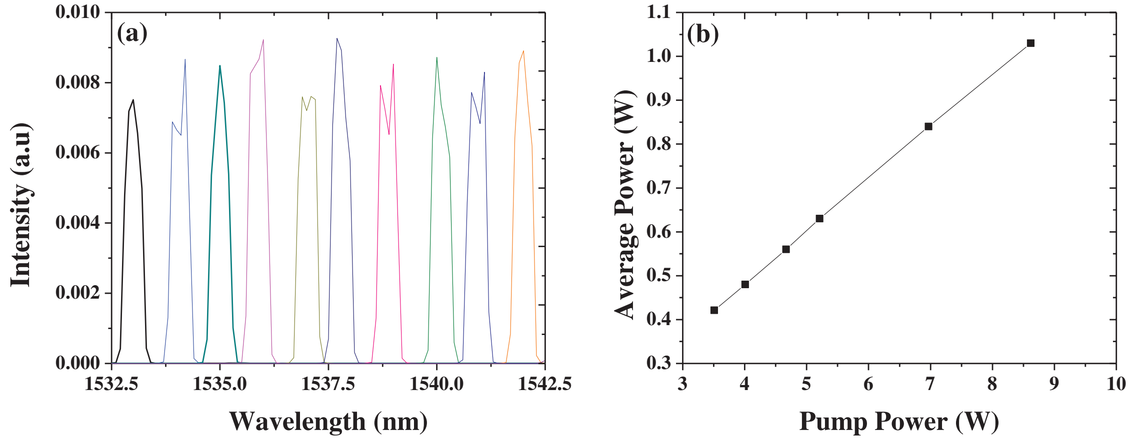

Figure 3. (*a*) Output spectra for the Q-switch tuning wavelength. (*b*) Spectral lasing of the pulsed laser at 1537.8 nm with 120 kHz repetition rate.

to 1532 nm) and on the other hand applying stretching the Bragg wavelength moves to larger wavelengths (1537.8 to 1542 nm), as shown in figure 2(*a*). The displacement of the micrometric screw was 80 μm for both compression and stretching. The average output power was ~0.7 W for a pump power of 8.6 W. The slope efficiency was ~8% because of the high laser threshold (~4.5 W) (see figure 2(*b*)).

In a second experiment, we introduced the AOM in the linear cavity to get the Q-switching and obtain pulses at the Bragg wavelength (1537.8 nm). In the same way as in the first experiment we applied compression and stretch laterally on the FBG and we obtained a range of tuning from 1532 to 1542 nm, with a displacement of ~0.1 nm per 10 μm in the micrometric screw, for a total displacement of 80 μm of the micrometric screw, for both compression and stretch. The spectral bandwidth in pulsed mode was 0.45 nm for each wavelength tuned. Figure 3(*a*) illustrates the wavelength tuning in the actively Q-switched laser. For both experiments we were limited by compression and stretching in the FBG, in order to avoid ruptures. We can observe two peaks for each selected wavelength. This feature is due to external birefringence induced in the grating by a sheet in which is placed the FBG and its being subjected to bending by moving the micrometer screw, compression and stretching that occurs in the FBG. In addition to this, the intrinsic birefringence of the grating causes the reflection spectrum of the grating to display peaks which appear in every wavelength tuned and which were measured by the OSA. Those peaks could be observed when we changed the resolution of the OSA from 0.1 to 0.03 nm.

In summary, these two experiments allowed us to tune the laser over the Er gain band, so the tuning of the laser was checked at CW and pulsed mode. In either case the laser can be tuned over approximately 12 nm over the erbium gain band. In figures 4(*a*) and (*b*), an interesting phenomenon is observed, repeatable for both CW and pulse mode, where the laser is emitting at three different wavelengths, because of the elastic behavior of the silica. This behavior leads to variations in the elastic deformation in the silica of the FBG, so that the spectral response of the grating suffers an induced deformation in the Bragg wavelength and the induced deformation generates some emission at other wavelengths that in our case were three emission wavelengths in the fiber laser [22]. These three wavelengths (at 1537.3, 1550.8 and 1552.2 nm) are presented for both CW and pulsed mode. They appear after a micrometer screw displacement of 90 μm for both compressing and stretching of the FBG, for the shortest and largest tuned wavelength in the CW and pulsed modes of the fiber laser, respectively. In figure 4 we can observe and compare the initial and

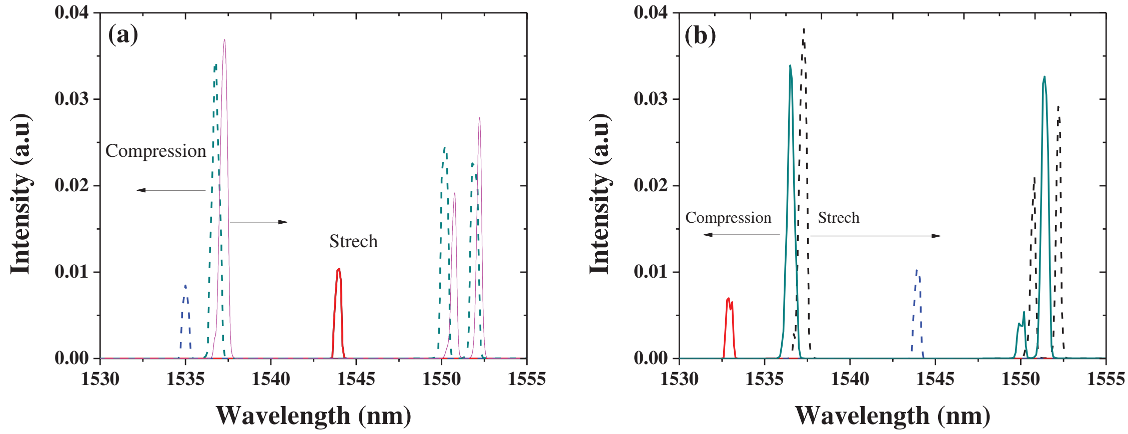

Figure 4. (*a*) Three-wavelength emission in CW mode and tuning range from 1532 to 1542 nm (blue broken curve and red full curve). (*b*) Pulsed mode at 120 kHz and tuning range from 1532 to 1542 nm (red full curve and blue broken curve), for a smallest and largest tuned wavelength in the Q-switched fiber laser.

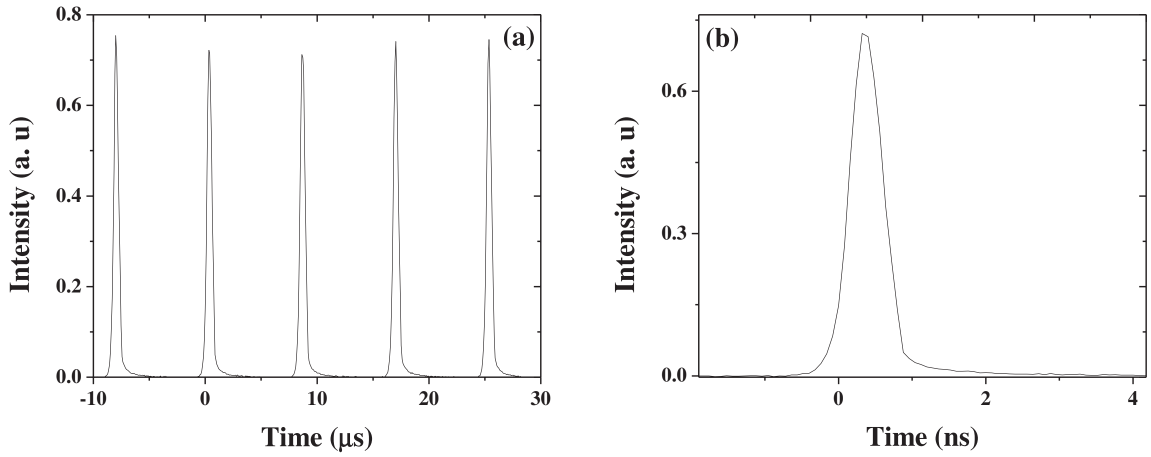

Figure 5. (*a*) Typical pulse train for 1.03 W output power, at 1537.8 nm. (*b*) Single pulse envelope and pulse duration of ~420 ns.

final tuning emission from ~1535 to 1542 nm for CW (figure 4(*a*), blue broken curve and red full curve) and from ~1532 to 1542 nm for pulse mode (figure 4(*b*), red full curve and blue broken curve).

Figure 5(*a*) shows a pulse train at a repetition rate of 120 kHz at 1537.8 nm and 1.03 W average output power. Figure 5(*b*) shows a pulse envelope having a full width high maximum (FWHM) of 420 ns, comparable to the Q-switched fiber laser reported in [23]. The laser efficiency was about 12% in pulsed mode.

The threshold power to achieve lasing is approximately 3.5 W for the Er/Yb doped fiber laser operating at 1537.8 nm. The scope trace was without significant amplified spontaneous emission (ASE) between pulses, thus the average output power was not significantly affected by ASE. Figure 6 shows the behavior of the average output power in CW and pulsed regimes as a function of the tuning wavelength. As shown in figure 6, the maximum average power of 1.03 W is obtained of 8.6 W pump power at 976 nm by using a FBG in pulsed mode at 1537.8 nm. The peak power is higher for shorter wavelength due to the gain spectrum of the Er/Yb doped fiber.

Figure 7 shows the variation of the average power and pulse duration as function of the pump power. We can observe that when we increase the pump power to 8.6 W we obtain a reduced pulse duration of 420 ns. This is because when we increase the pump power, the optical gain in the

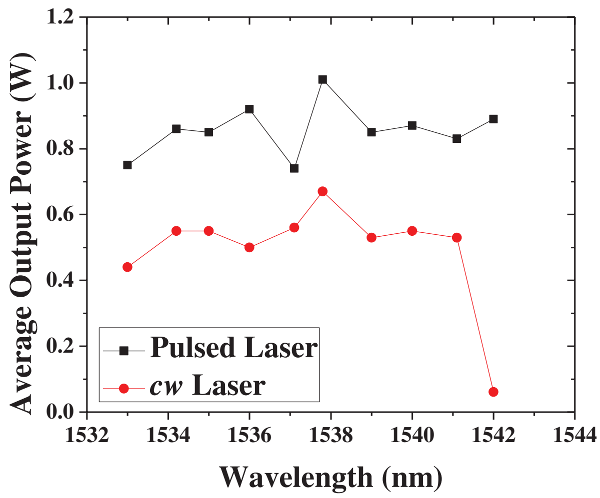

Figure 6. Characteristic of the average output power as a function of lasing wavelength for 8.6 W pump power for CW and pulsed regimes.

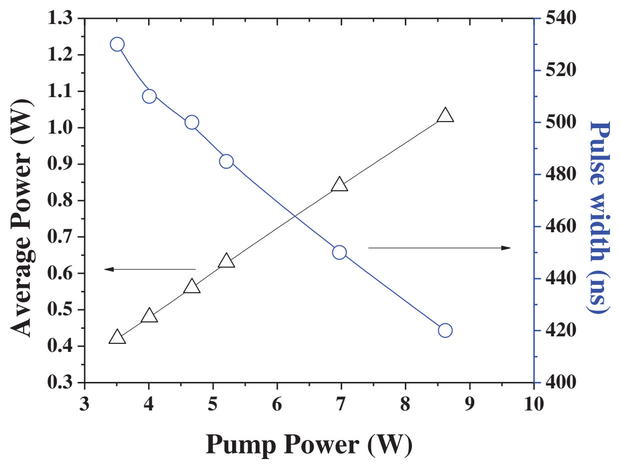

Figure 7. Characteristic of the average power and pulse duration as a function of pump power at 120 kHz.

erbium doped fiber increases. This increase reduces the establishing time of the pulse and therefore the pulse duration decreases.

Additionally it can be seen in figure 7 that when we increase the pump power the output power increases too. That is due to the fact that higher pump power contributes to higher peak power of the laser pulses [24]. Finally we can note that if we optimize the losses in the cavity of the laser, we can expect also to improve the laser efficiency.

4. Conclusion

In conclusion, we have demonstrated a simple double-clad Er/Yb tunable fiber laser source (in CW and pulsed modes), which is formed by a FBG and dichroic mirrors at the end of the laser with a 3 dB output coupler. The performance of the laser was investigated for different tuned wavelengths. The slope efficiencies of the tunable Er/Yb doped fiber laser are obtained at 8 and 12% for CW and pulsed modes, respectively, using a FBG at 1537.8 nm. The highest efficiency is obtained when the laser operates at a wavelength of 1537.8 nm with a spectral bandwidth of 0.17 and 0.45 nm in CW and pulsed modes, respectively. The threshold power to achieve lasing is approximately ~4.5 and ~3.5 W for CW and pulsed modes of the laser, respectively. The efficiency is higher at shorter wavelength operation due to the gain characteristic of the Er/Yb doped fiber. The tuning range was about 12 nm for both CW and pulsed modes. In pulsed mode we obtained a minimum pulse duration of ~420 ns at 120 kHz with 1.03 W average output power. The laser was designed for application in spectroscopy and as a tunable source for THz applications.

Acknowledgments

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