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Self-Q-switched Er–Yb double clad fiber laser with dual wavelength or tunable single wavelength operation by a Sagnac interferometer

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Abstract

We report a self-Q-switched Erbium-Ytterbium-doped double cladding fiber ring laser with dual wavelength or tunable single wavelength operations. A Sagnac interferometer with a high birefringence fiber in the loop was used for the wavelength tuning of the single line operation and cavity loss adjustment for dual wavelength laser operation. Single wavelength laser operation for a pump power of 421 mW tunable in a range of 1561.4 nm to 1569.8 nm and dual wavelength laser operation at 1561.1 nm and 1571.4 nm with equal output powers are presented.

Keywords: self-Q-switching, Sagnac interferometer, Er/Yb fiber lasers

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

1. Introduction

Q-switched fiber lasers are attractive optical sources for applications in remote sensing, medicine, and terahertz generation, among others. The Q-switching technique in fiber lasers has been studied extensively [1–3]. Typically, this technique is used to obtain higher pulse energies at a repetition rate around 100 kHz, and pulse duration in the nanoseconds range. Several passive and active Q-switching methods for fiber lasers have been reported [4–11]. Experimental setups for passive Q-switched fiber lasers include the use of carbon nanotubes or graphene acting as saturable absorbers [12–16]. In this case, the pulse characteristics are modified by pump power. Commonly, passive Q-switching lasers have the advantage of a simple design and low cost since they do not require the use of modulators and its electronics. It was also demonstrated that Q-switched pulses can be generated by unpumped sections of a rare-earth-doped fiber used as saturable absorbers. This passive Q-switched technique called self-Q-switching (SQS) has also been reported [17–22]. Kir'yanov has studied pulsed laser operation implying the power-dependent thermo-induced lensing in an all-fiber Erbium laser [17]. Zhang in [22] has presented a SQS all-fiber laser using a long segment of Erbium/Ytterbium double cladding (EYDC) fiber in a ring fiber laser incorporating a Mach-Zehnder interferometer. To the best of our knowledge, stable fiber lasers by SQS technique with a dual-wavelength or tunable single-wavelength operation, have not been yet reported.

In this paper, we experimentally demonstrate dual-wavelength or tunable single-wavelength laser operations with the SQS technique in a ring cavity fiber laser using an EYDC fiber as a gain medium. A Sagnac interferometer (SI) is used as a spectral filter. The SI loop includes a Hi-Bi fiber and has a periodic dependence of the reflection/transmission on the wavelength. The dependence can be shifted by changing the temperature of the Hi-Bi fiber which allows dual-wavelength or single tunable wavelength generation [23]. When the temperature of the Hi-Bi fiber is 20 °C and at the maximal pump power of 575 mW, stable SQS laser emission at 1565.15 nm, with a repetition rate of 25 kHz and pulse duration of 4.1 μs is observed. The single wavelength can be tuned in a range from 1561.4 nm to 1569.8 nm by temperature variations of the Hi-Bi fiber from 15.8 °C to 23 °C. Stable dual wavelength laser operation with equal output powers is generated at 1561.1 nm and 1571.4 nm, with temperatures of 15.4 °C and 23.5 °C. The difference of 8.1 °C corresponds to the displacement of the SI spectrum by one period.

2. Experimental setup

The proposed experimental setup is presented in figure 1. The cavity includes a 3-m length of EYDC fiber (CoreActive DCF-EY-10/128) with core numerical aperture of 0.20, core diameter of 10 μm and outer clad diameter of 128 μm. The EYDC fiber is used as a gain medium. An un-pumped section of the same fiber also acts as a saturable absorber. The EYDC fiber is pumped at 976 nm by a multimode high-power source through a beam combiner. The ring cavity is completed by a Sagnac interferometer with Hi-Bi fiber in the loop (Hi-Bi SI), the 50/50 coupler 2, and a fiber isolator. The Hi-Bi SI formed by the 50/50 coupler 1 whose output ports are connected by ~55 cm of Hi-Bi fiber with birefringence of 4.125×10^{-4} is used as spectral filter with periodical transmission spectrum. The spectrum can be displaced by temperature changes of the Hi-Bi fiber. The coupler 2 output port is used to measure the output laser power and the spectrum by a photodetector (observed on an oscilloscope) and by an OSA, respectively.

3. Experimental results and discussion

The calculated Hi-Bi SI wavelength transmission period is ~10.6 nm and the temperature period is 8.1 °C [23]. Figure 2 shows the Hi-Bi SI transmission spectrum measured at the output port of the coupler 2. The measurements were performed with the cavity open between the coupler 2 and the isolator with an ASE as an input signal when the pump power is below the laser threshold. The temperature of the Hi-Bi fiber loop was 22.3 °C. Measurements were performed in the range from 1539 nm to 1564 nm by an OSA. The SI was adjusted to have maximum contrast between maximum and minimum transmission [23]. As it is seen, the measured spectrum period is ~10.3 nm. The SI spectrum can be displaced by fiber loop temperature changes [23]. This SI feature is used for laser wavelength tuning.

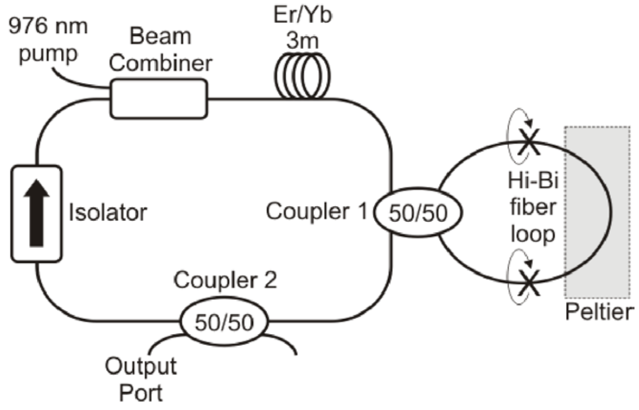

Figure 1. Self Q-switched fiber laser experimental setup.

Figure 3 shows the measured pulses for single wavelength laser operation. The experimental results were obtained at a Hi-Bi fiber temperature of 20ºC in which lasing is generated at 1565.15 nm. Figure 3(a) shows the pulse trains for pump power variations in a range from 193 mW to 575 mW where stable SQS pulses are observed. As it can be seen, when pump power increases, both repetition rate and pulse peak power increase. With pump powers above 600 mW the laser is operating in CW regime (the un-pumped doped-fiber section acting as a saturable absorber is not long enough to generate SQS pulses at high pump power). On the other hand, with pump power below 193 mW, laser emission is not generated. Figure 3(b) shows the dependence of the repetition rate and the pulse duration on pump power variations. As it is shown, for the minimal pump power of 193 mW in which SQS pulses are generated, pulse duration is ~12 μs with a repetition rate of 6 kHz. For the maximal launched pump power of 575 mW in which pulses are observed, pulse duration is ~4.1 μs with a repetition rate of 25 kHz.

Figure 4 shows the dependence of the wavelength of the SQS laser on the temperature of the Hi-Bi fiber in the SI loop. The pump power was 421 mW. The results show that with the increase of temperature from 15.8 °C to 23 °C, the laser line shifts toward shorter wavelengths, from 1569.8 nm to 1561.4 nm. As it can be seen, at temperatures of 15.4 °C and 23.5 °C, dual wavelength operation with equal powers at 1571.4 nm and 1561.1 nm is observed. The simultaneously generated wavelengths approximately correspond to the maxima of the SI transmission. The separation between the generated wavelengths coincides with the Hi-Bi SI spectrum period of 10.3 nm. Dual wavelength laser operation is repeated for each 8.1 °C of the temperature change of the Hi-Bi fiber. For these temperatures two laser lines have the same conditions for generation. When the SI transmission spectrum moves to longer wavelengths (lower temperature) or to shorter wavelengths (higher temperature) the laser line between 1561.4 nm and 1571.4 nm has preferable conditions for generation than the laser line longer than 1571.4 nm or shorter than 1561.4 nm, and single line generation is observed.

Figures 5(a) and (b) show the dependence of the repetition rate and the pulse duration respectively on the pump power measured for the laser tuned to different wavelengths.

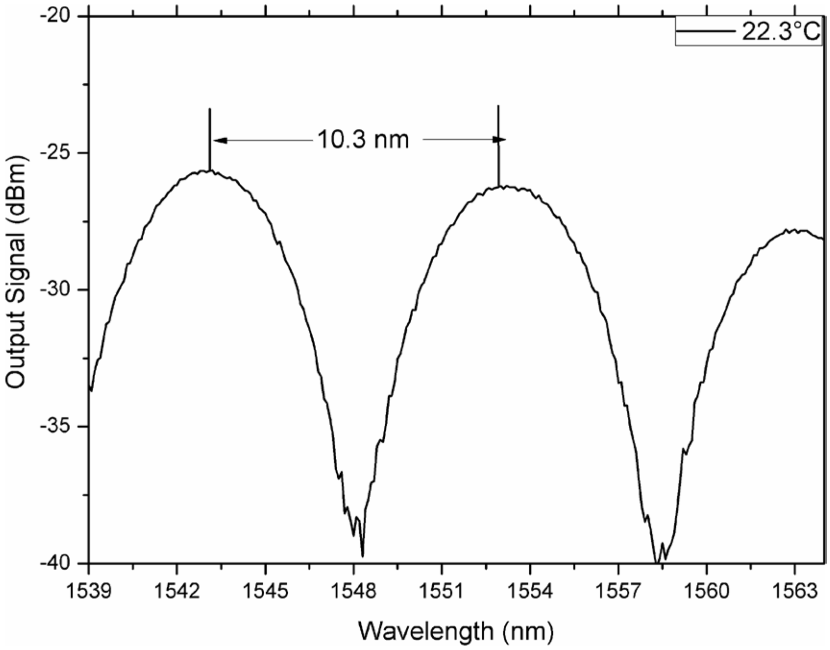

Figure 2. Hi-Bi SI output signal spectrum.

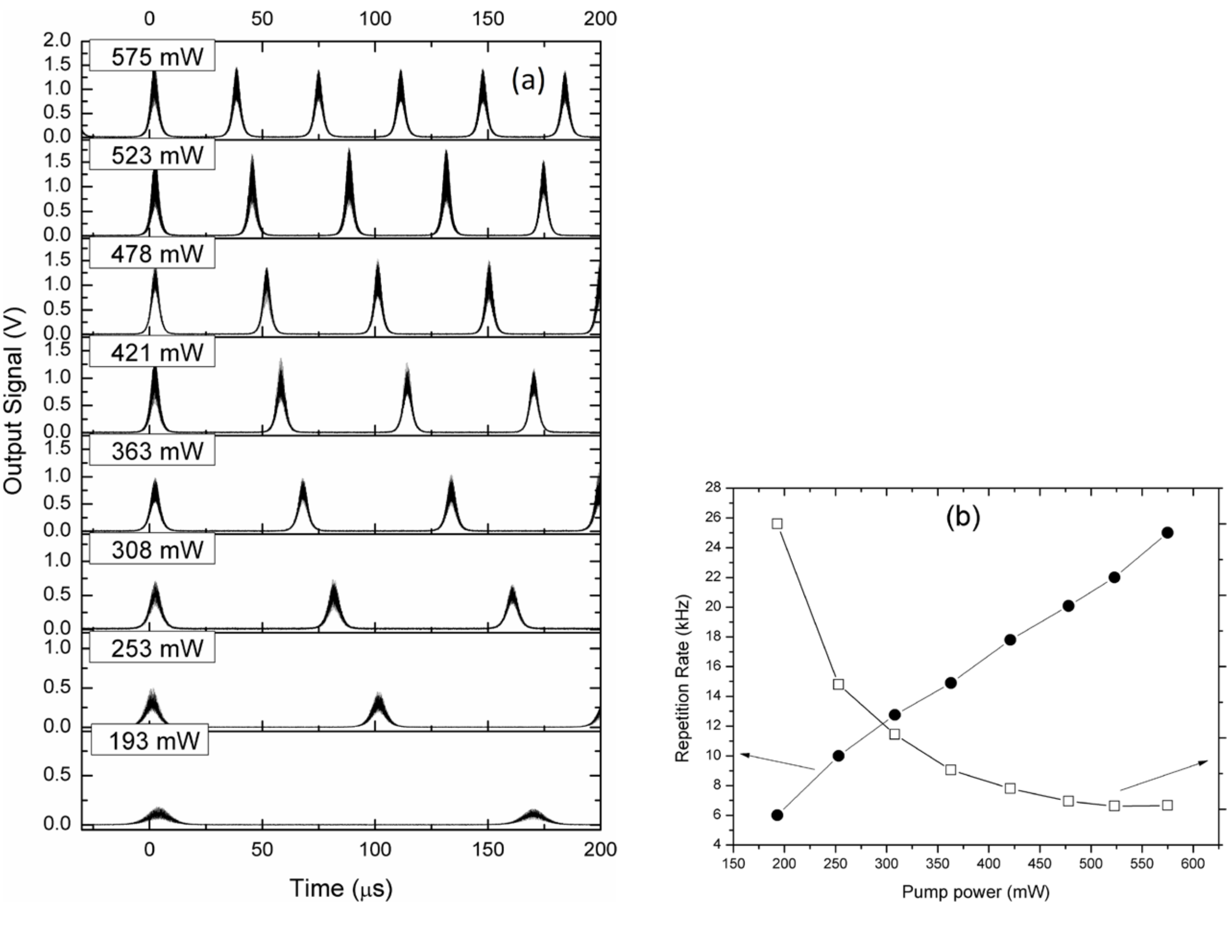

Figure 3. SQS fiber laser single wavelength operation tuned at 1565.15 nm under pump power variations, (a) pulses profiles, (b) dependence of the repetition rate and pulse duration on pump power.

We perform the measurements for a wavelength range from 1561.3 nm to 1569.1 nm and for a pump power range from 193 mW to 478 mW. As it is shown, when we increase the pump power, the repetition rate increases and the pulse duration decreases. With the laser line tuning to longer wavelengths, pulse duration increases slightly. As it can be seen the

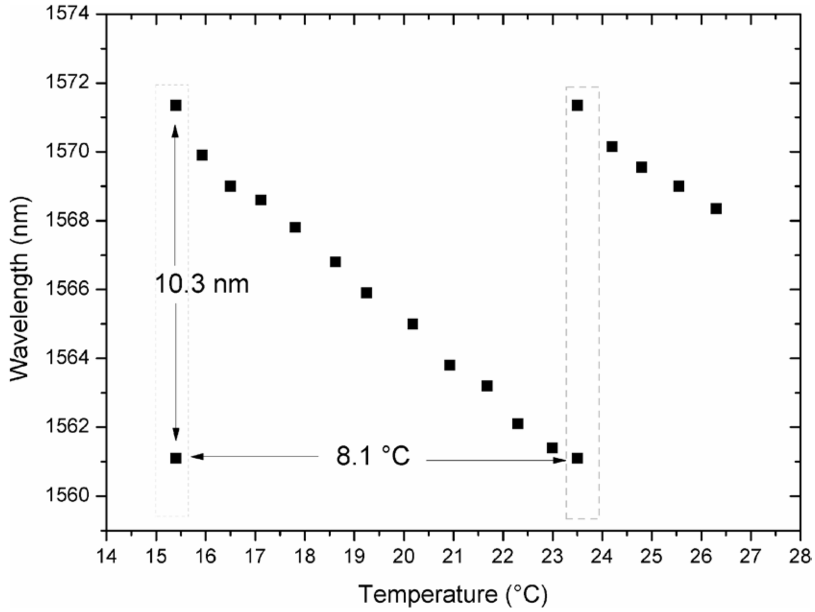

Figure 4. SQS pulsed laser spectrum by Hi-Bi SI temperature variations.

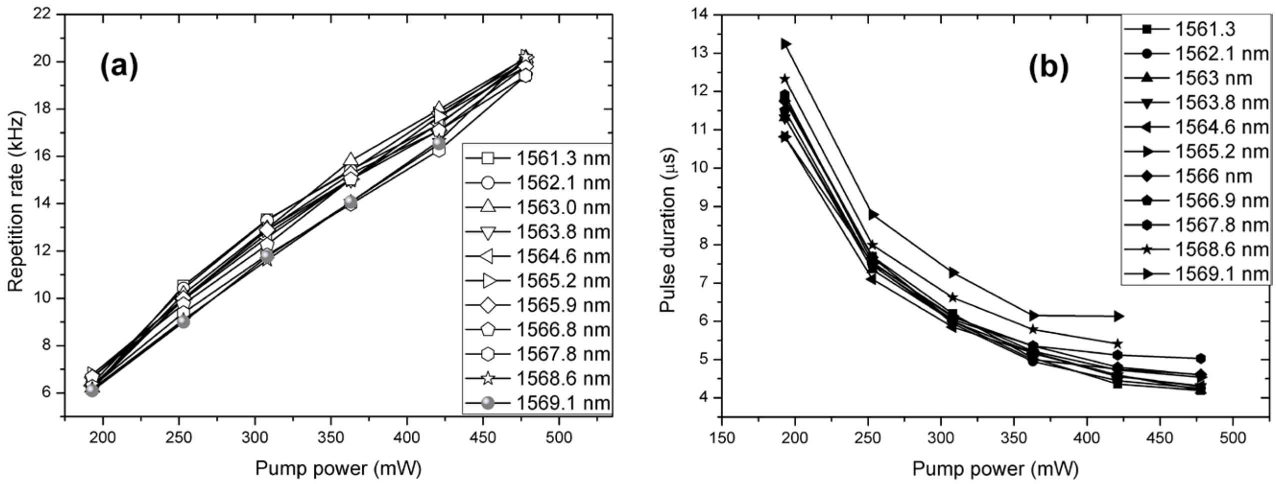

Figure 5. SQS single wavelength laser operation on wavelength tuning and pump power variations, (a) repetition rate, (b) pulse duration.

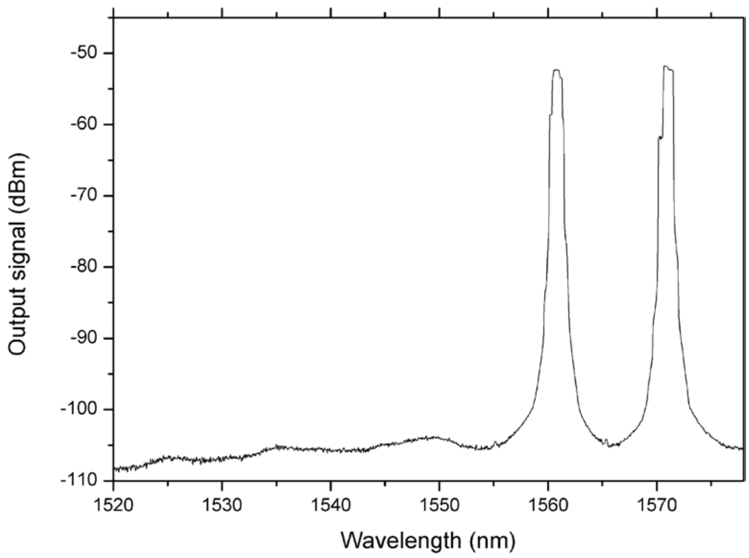

Figure 6. SQS laser spectrum for dual wavelength operation.

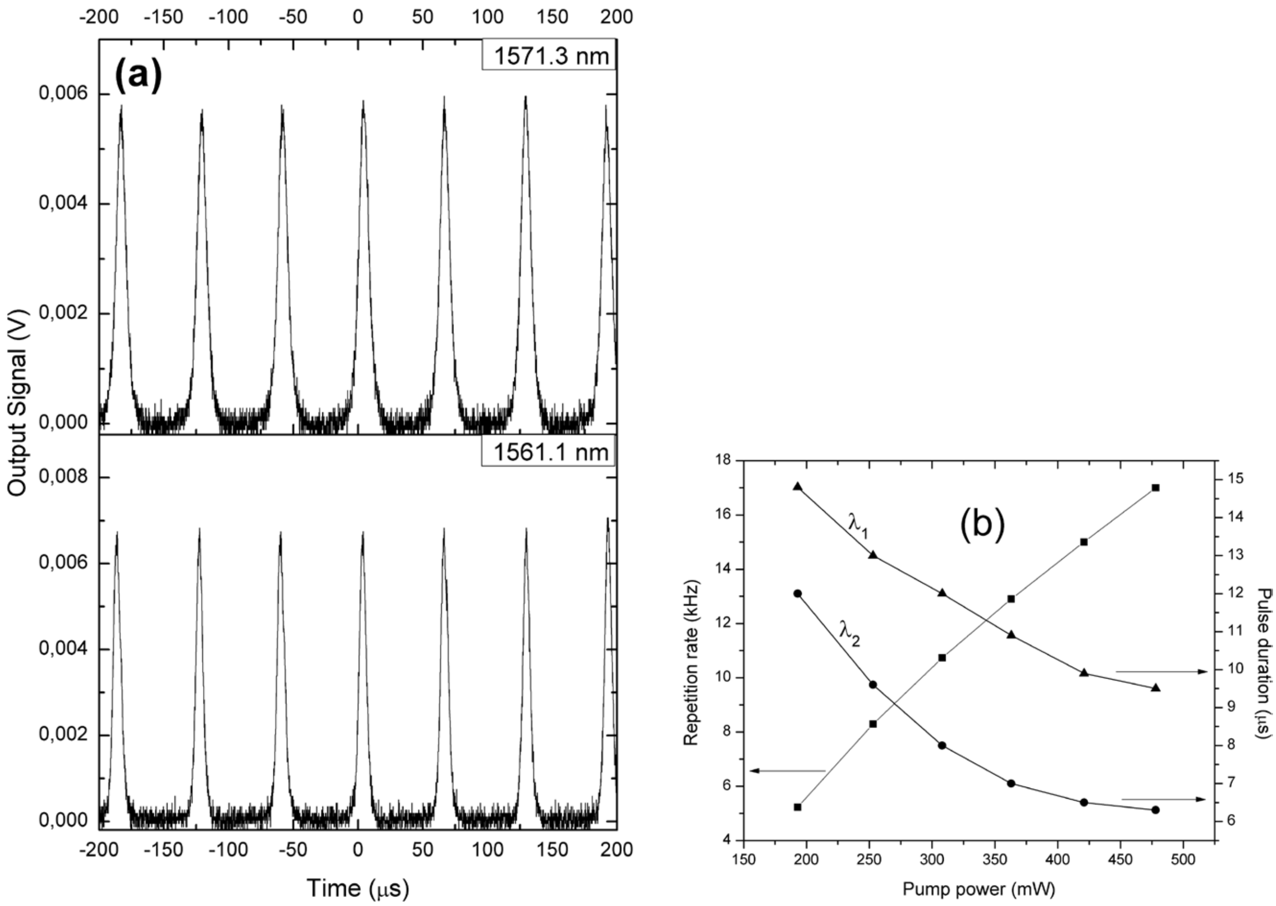

Figure 7. SQS dual wavelength laser operation, (a) Pulse train for each generated wavelength, (b) repetition rate and pulse duration versus pump power for lines at 1571.3 nm and 1561.1 nm.

effect of the wavelength tuning on the pulse repetition rate and the pulse duration is not significant.

At 23.5 °C the laser generates two wavelengths with equal powers. Figure 6 shows the measured spectrum for dual wavelength emission. The spectrum was measured at a pump power of 484 mW. Laser lines with equal powers are centred at 1561.1 nm and 1571.4 nm.

Figure 7 shows the experimental results for SQS dual-wavelength laser operation. Figure 7(a) shows the pulse trains for each generated wavelengths (individually filtered by a monochromator) with a pump power of 421 mW. The generated laser lines at 1561.1 nm and 1571.3 nm present similar repetition rates of ~15 kHz. Figure 7(b) shows the dependencies of the repetition rate and pulse durations on pump power. The pulses for each line were filtered by the monochromator. As it can be seen, the repetition rate for each wavelength varies approximately over the same range from 5 kHz to 18 kHz as in the case of single wavelength operation. For the line at 1561.1 nm the pulse duration lies in a range from 6.3 μs to 12 μs, and for the line at 1571.3 nm in a range from 9.5 μs to 14.7 μs. The measurements were performed with a pump power variation from 193 mW to 478 mW. The pulse duration for the longer wavelength is longer than for the shorter wavelength, as it can also be noticed from figure 7(a).

4. Conclusions

We have experimentally demonstrated a stable SQS ring cavity fiber laser with dual-wavelength or tunable single wavelength operations based in an EYDC fiber as a gain medium with an un-pumped section acting as a saturable absorber. A Hi-Bi SI is used for wavelength tuning in single wavelength operation and for cavity loss adjustment for simultaneous dual wavelength operation. With a pump power of 575 mW, stable SQS pulses with duration of 4.1 μs and repetition rate of 25 kHz are obtained at room temperature. Tunable single wavelength laser operation with pump power of 421 mW, is possible over a range of ~8.4 nm with temperature changes in a range of ~7.2 °C. Dual wavelength laser operation is generated at 1561.1 nm and 1571.4 nm with temperatures of 15.4 °C and at 23.5 °C corresponding to the SI spectrum displacement by one period of 10.3 nm.

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