Actively Q-switched dual-wavelength laser with double-cladding Er/Yb-doped fiber using a Hi-Bi Sagnac interferometer

2015 Laser Phys. Lett. 12 025102

(http://iopscience.iop.org/1612-202X/12/2/025102)

IOP Publishing | Astro Ltd Laser Physics Letters

Laser Phys. Lett. **12** (2015) 025102 (6pp) doi:10.1088/1612-2011/12/2/025102

Actively Q-switched dual-wavelength laser with double-cladding Er/Yb-doped fiber using a Hi-Bi Sagnac interferometer

M Durán-Sánchez[1,2], R I Álvarez Tamayo[2], O Pottiez[3], B Ibarra-Escamilla[2], J C Hernández-García[1,4], G Beltran-Perez[5] and E A Kuzin[2]

[1] Consejo Nacional de Ciencia y Tecnología (CONACYT), Av. Insurgentes Sur No. 1582, Col. Crédito Constructor, Del. Benito Juárez, C. P. 039040, Mexico
[2] Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), L. E. Erro 1, Sta. Ma. Tonantzintla, Pue. 72824, Mexico
[3] Centro de Investigaciones en Óptica (CIO), Loma del Bosque 115, Col. Lomas del Campestre, León, Gto. 37150, Mexico
[4] Departamento de Electrónica, División de Ingenierías Campus Irapuato-Salamanca, Universidad de Guanajuato, Carretera Salamanca-Valle de Santiago Km 3.5 + 1.8 Km, Comunidad de Palo Blanco, Salamanca, Gto. 36885, Mexico
[5] Benemérita Universidad Autónoma de Puebla, Facultad de Ciencias Físico Matemáticas, Av. San Claudio y Rio Verde, San Manuel, Puebla, 72000, Mexico

E-mail: mduransa@conacyt.mx

Received 4 December 2014, revised 10 December 2014
Accepted for publication 12 December 2014
Published 9 January 2015

Abstract

An actively Q-switched double-wavelength Er/Yb fiber laser is experimentally demonstrated. The linear cavity is formed by a pair of fiber Bragg gratings on one side and a Sagnac interferometer (SI) with high birefringence fiber in the loop on the opposite side. A 3 m of double-cladding Er/Yb-doped fiber used as a gain medium is pumped by a 978 nm laser diode. The SI is used to adjust the internal cavity losses for simultaneous dual-wavelength laser generation. The adjustment is performed by temperature variations of the high birefringence fiber in the SI loop. The maximum average output power for the Q-switched laser operation in dual-wavelength mode was around 68 mW with a repetition rate of 40 kHz for 2 W of pump power. The minimum pulse duration was around 280 ns. The maximum pulse energy was 1.75 μJ.

Keywords: fiber lasers, Q-switching, gratings, modulation, cavities, Sagnac interferometer

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

1. Introduction

Actively Q-switched fiber lasers have been attracting attention due their potential applications in different areas such as LIDAR, remote sensing, medical systems and terahertz generation, among others. 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 in all-fiber and integrated optics experimental setups. Several free space or all-fiber laser designs have been proposed for Q-switched lasers. They use fibers doped with different rare earth elements as gain medium and different active Q-switching modulation optical devices [1–11]. Most of the investigations use single mode fiber. On the other hand, double-clad fibers (DCF) offer high conversion efficiency for the generation of high-energy pulses, making them an attractive gain medium for pulsed fiber lasers [12–18]. Different experimental setups of actively Q-switched fiber lasers using Ho- and Tm-doped fibers, bismuth based Er-doped fiber and DCF have also been recently reported [16–19].

Nowadays, simultaneous dual-wavelength pulsed lasers have been of interest due to their potential application in THz

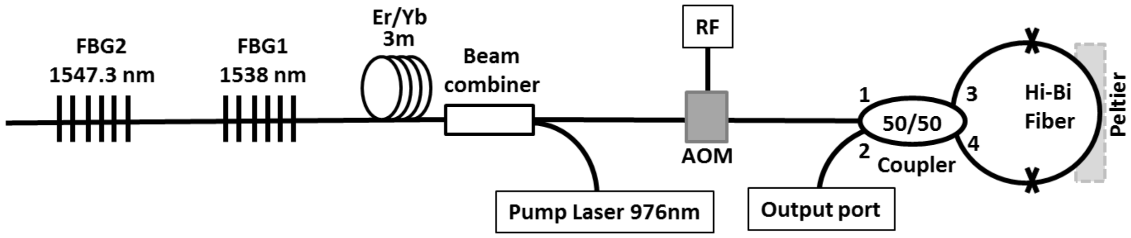

Figure 1. Q-switched fiber laser experimental setup.

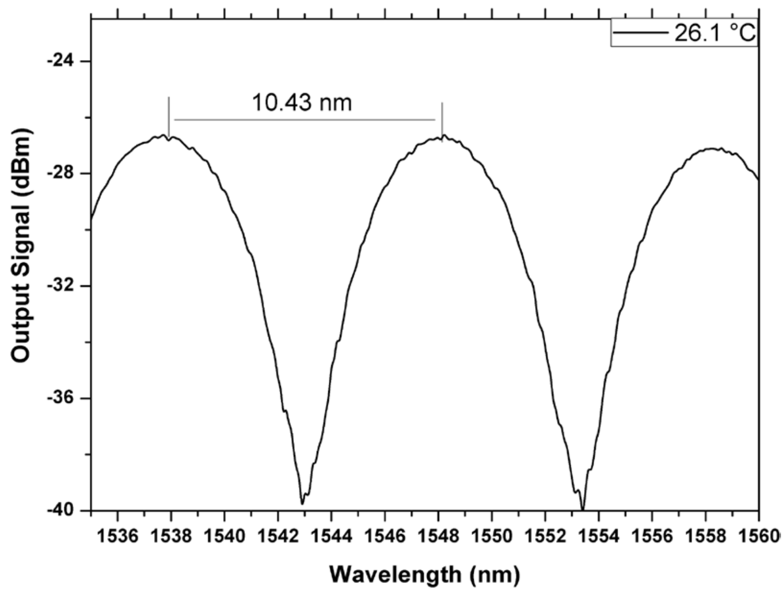

Figure 2. SI output signal spectrum.

generation research and spectral analysis, among other fields. Regarding dual-wavelength pulsed laser emission by using active Q-switching techniques, a ring cavity dual-wavelength fiber laser with wavelength spacing of 2.2 nm [20], a cascade configuration pulsed laser using Ho^{3+} doped fiber operating in the mid-infrared emitting at 3.005 and 2.074 μm [18] and a linear cavity configuration using Er/Yb DCF as a gain medium with tunable dual-wavelength laser generation [21], have been reported previously.

In this letter, we present a stable actively Q-switched Er/Yb DCF laser with single and dual-wavelength laser operations by intra-cavity loss adjustment through the use of a Sagnac interferometer (SI), applying temperature variations on the high birefringence (Hi-Bi) fiber loop. For dual-wavelength pulsed laser operation with wavelength separation of 9.3 nm, the maximal achieved pulse energy of 1.75 μJ is obtained with pulse duration of 280 ns at a repetition rate of 40 kHz.

2. Experimental setup

The proposed experimental setup is presented in figure 1. The linear laser cavity is formed by a pair of fiber Bragg gratings (FBG) on one side and a SI with Hi-Bi fiber in the loop on the other side. The SI consists of a 50/50 coupler with output ports connected by a 55 cm Hi-Bi fiber with birefringence of 4.125×10^{-4} and has a reflection spectrum presenting a sinusoidal dependence on the wavelength. The Hi-Bi fiber is placed on a Peltier cooler to control the temperature of the Hi-Bi fiber and to shift the spectral dependence of the SI [22]. Splices between Hi-Bi fiber and coupler output ports are placed in mechanical rotation stages for adjustment of the transmission spectrum contrast [22]. The gain medium is a 3 m long Er/Yb-codoped DCF pumped at 978 nm by a multimode high-power laser through a beam combiner. For Q-switched laser operation, a fiber-pigtailed acousto-optic modulator (AOM) is used. The FBGs with central reflection wavelengths at 1547.3 and 1538 nm have approximately 99% of maximum reflection. The 50/50 coupler port 2 (output port) is used to measure the output laser power and SI transmission spectrum with an OSA and also the pulses are detected by a photodetector and are observed on an oscilloscope.

3. Experimental results and discussion

With the mentioned characteristics, the SI reflection spectrum is a sinusoidal function whose calculated period is 10.5 nm [22]. Figure 2 shows the spectrum of the output signal with an ASE input signal obtained from the DCF when the pump power is below the laser threshold. Measurements were performed in the range between 1535 and 1560 nm by an OSA at

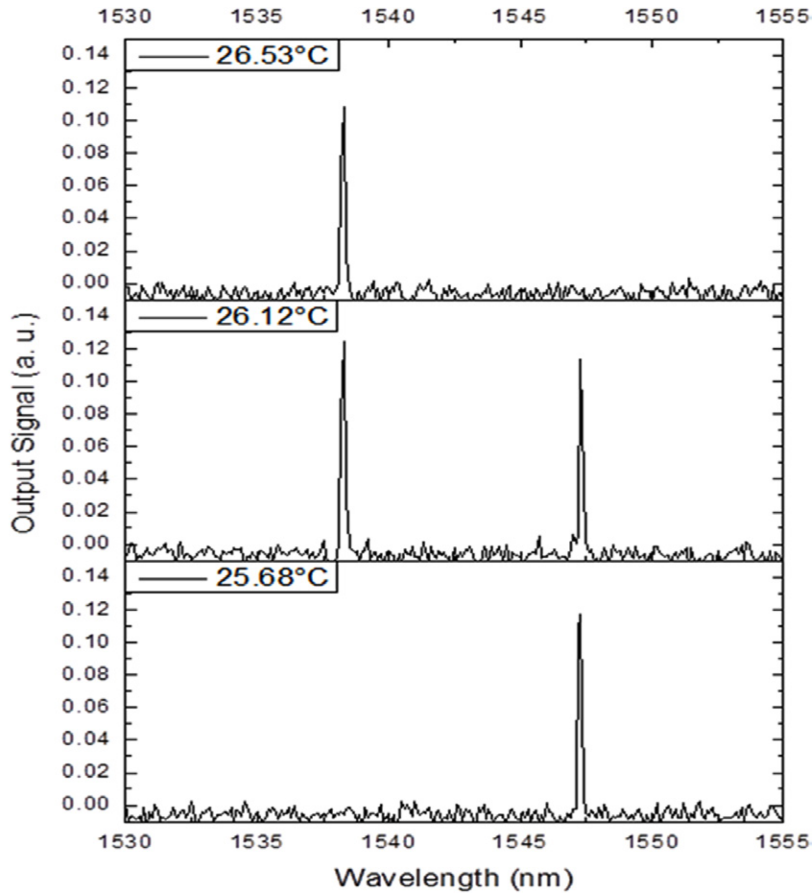

Figure 3. Q-switched fiber laser optical spectrum measurement with single- and dual-wavelength operation.

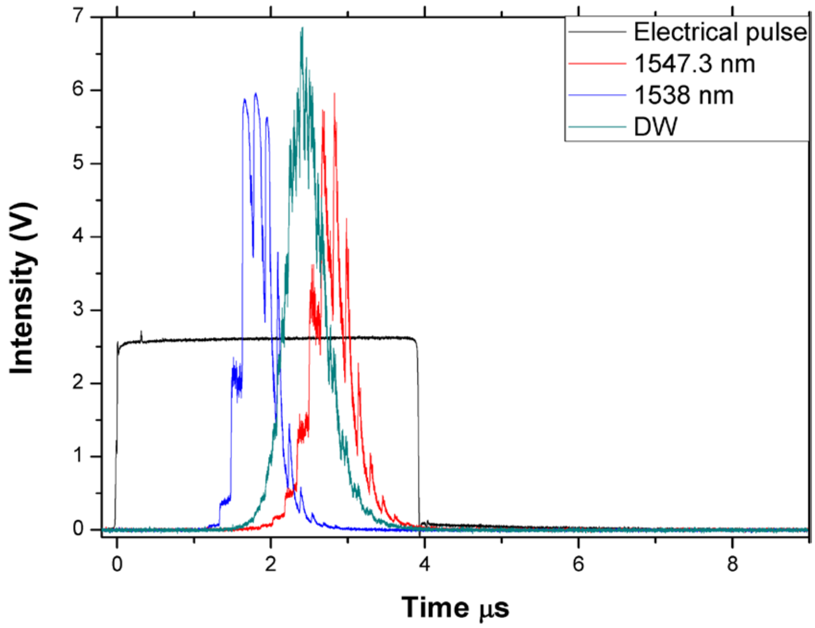

Figure 4. Pulses measured for single- and dual-wavelength laser operation modes. Electrical pulse (black line), single-wavelength operation at 1547.3 nm (red line) and 1538 nm (blue line), dual-wavelength (DW) operation (green line).

the temperature of the Hi-Bi fiber in the loop equal to 26.1° C. The measured period is 10.43 nm. The SI was adjusted to have maximum contrast between maximum and minimum transmission. The wavelength separation between FBG central reflections is around 9.3 nm and the SI wavelength period is 10.43 nm; because these values are different, the ratio between the SI reflection values at the two FBG wavelengths can be varied, which in turn allows equilibrating the internal cavity

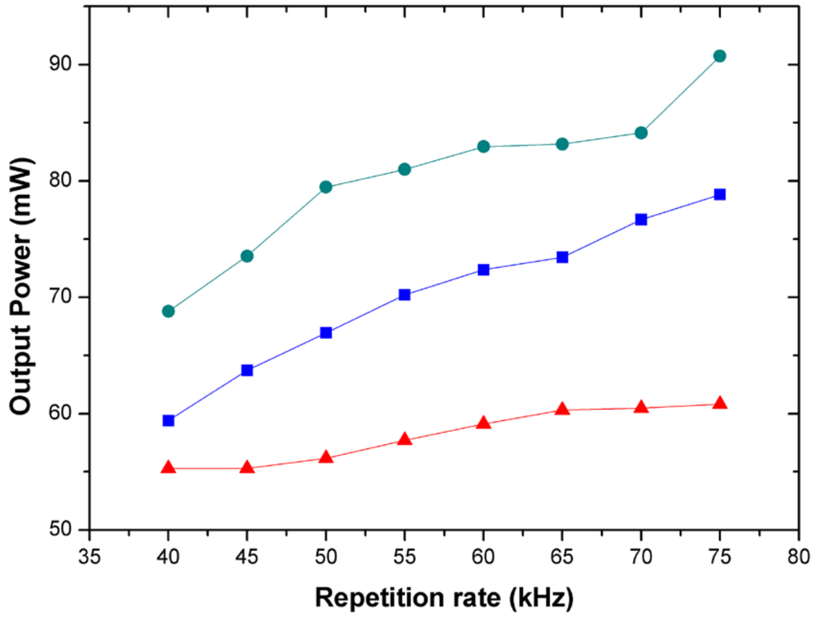

Figure 5. Q-switched laser average power measurements with repetition rate variations for single- and dual-wavelength laser operations. Single-wavelength operation at 1547.3 nm (red line) and 1538 nm (blue line), dual-wavelength operation (green line).

losses to obtain dual-wavelength laser operation with the proper SI spectrum wavelength displacement by fiber loop temperature changes.

Figure 3 shows the optical spectrum of the Q-switched fiber laser. Measurements were performed at the output port with an OSA with 2 W of pump power. As can be seen, single- and dual-wavelength laser operation is achieved. The operation mode is obtained by variation of the temperature of the Hi-Bi fiber in the SI loop. Single-wavelength laser operation at 1538 nm corresponding to FBG1 peak reflection is obtained at 26.53 °C; operation at 1547.3 nm corresponding to FBG2 is obtained at 25.68 °C. Stable dual-wavelength laser emission with equal powers is achieved at a temperature of 26.12 °C where cavity loss adjustment allows simultaneous dual-wavelength laser emission. The wavelength separation between simultaneously generated laser lines is 9.3 nm.

Figure 4 shows the laser pulses which correspond to the modes of operation presented in figure 3 with an electrical pulse time window of 4 μs (black line). As can be seen, the pulse generated with ~2 μs delay time with respect to the electrical pulse rising edge corresponds to the single laser line operation at 1538 nm (blue line). The pulse shown at 3 μs of delay time corresponds to single-wavelength operation at 1547.3 nm (red line). For dual-wavelength laser emission the pulse appears with an intermediate delay time of 2.5 μs (green line). The delay time displacement depends on the laser wavelength generated. The pulses have characteristic shapes of pulses generated by the active Q-switching technique.

Figure 5 shows the laser output powers as a function of repetition rate from 40 to 75 kHz. For single mode operation at 1538 nm the measured average power lies in a range from 59 to 78 mW and at 1547.3 nm from 55 to 61 mW. For dual-wavelength Q-switched laser operation the average power is in a range from 68 to 90 mW. These results show that for dual-wavelength laser operation the average power increases in comparison with single mode operation.

Figure 6 shows pulse duration and pulse energy as a function of the repetition rate for both single- and dual-wavelength laser operation with a pump power of 2 W. The pulse energy decreases when the repetition rate increases due to the decrease of the energy in the doped fiber as the time between pulses shortens. At the same time, the pulse duration increases as the repetition rate increases. Measurements were performed with a repetition rate in a range from 40 to 75 kHz. Figure 6(*a*) shows the results for single-wavelength operation at 1538 nm. In this case at the maximal repetition rate of 75 kHz the Q-switched laser generates pulses with duration and pulse energy of 0.6 μs and 0.93 μJ, respectively. For single-wavelength operation at 1547.3 nm the pulse energy of 0.75 μJ and the pulse duration of 0.53 μs are obtained at the maximal repetition rate of 75 kHz shown in figure 6(*b*). Figure 6(*c*) shows the measurements for dual-wavelength laser operation mode with pulse energies in a range from 1.75 to 1.1 μJ and pulse durations from 0.28 to 0.57 μs are obtained in a repetition rate range from 40 to 75 kHz, respectively. Pulse energy was estimated from average power and repetition rate measurements presented in figure 5.

Figure 7 shows the measured output pulse train in the time domain for dual-wavelength laser operation mode with a repetition rate of 55 kHz. The SI Hi-Bi fiber loop temperature is adjusted to 26.1 °C for equal power simultaneous dual-wavelength operation as shown in figure 3. With a decrease in the repetition rate, the laser pulses shift towards the electrical pulse rising edge, while with an increase in the repetition rate, the generated pulses shift to the electrical pulse falling edge. For repetition rates lower than 40 kHz and higher than

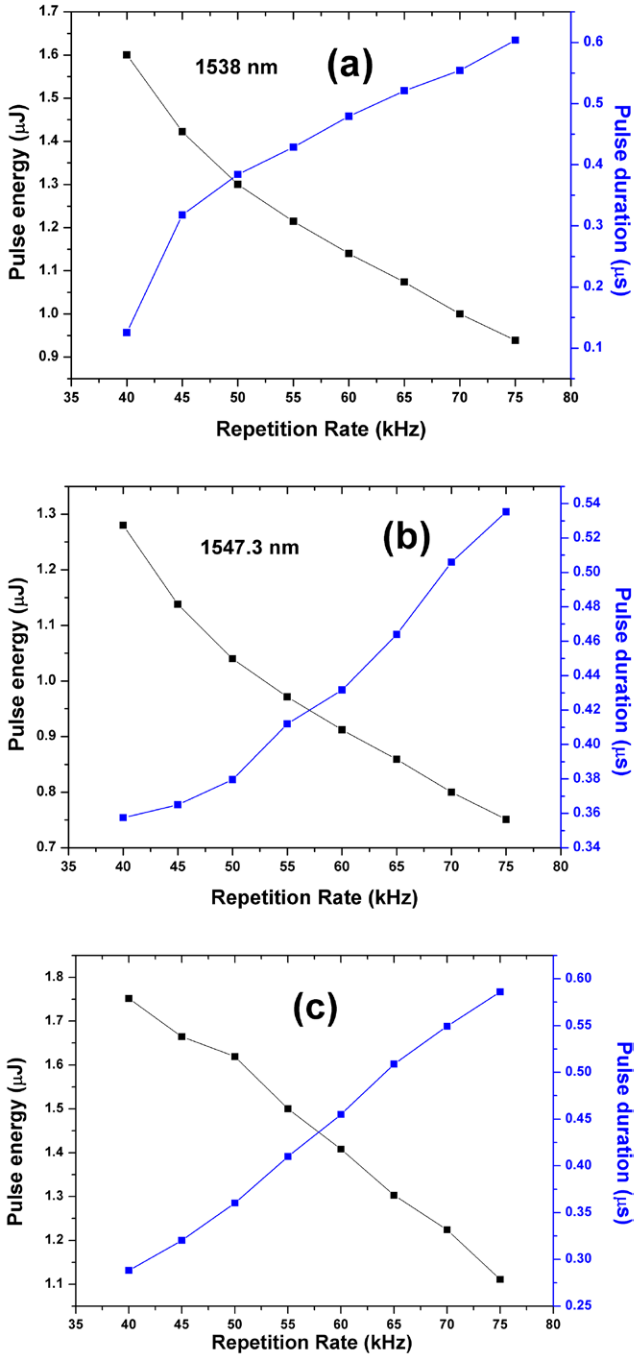

Figure 6. Pulse duration (blue line) and pulse energy (black line) as a function of the repetition rate for (*a*) single 1538 nm wavelength, (*b*) single 1547.3 nm wavelength and (*c*) dual-wavelength operation.

75 kHz, the laser pulses shift outside the time window generating unstable pulsed emission. Pulse train measurements show stable actively Q-switched laser operation in a range from 40 to 75 kHz.

4. Conclusions

In this letter, we have reported an actively Q-switched pulsed Er/Yb double clad fiber laser with single mode and simultaneous dual-wavelength laser operation using a SI with Hi-Bi fiber in the loop. Single- and dual-wavelength

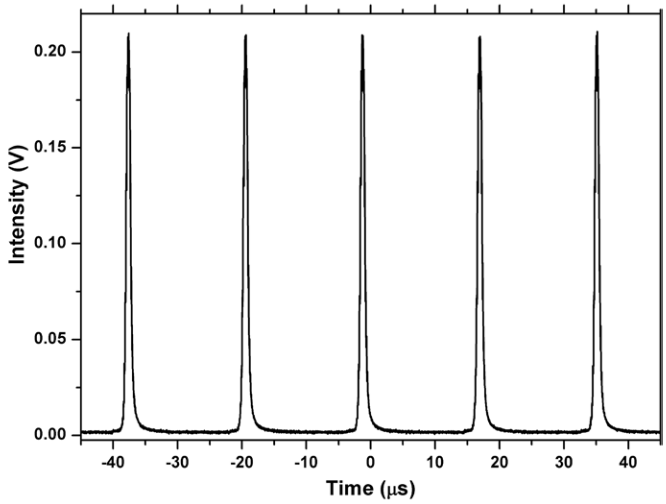

Figure 7. Measured pulse train for actively Q-switched dual-wavelength laser operation.

laser operation is achieved adjusting the internal cavity losses by Hi-Bi fiber loop temperature variations. The SI periodic transmission spectrum amplitude was adjusted for a maximal contrast by fiber loop twist. The output power achieved for Q-switched laser operation in dual-wavelength mode is in a range from 68 to 90 mW, the pulse energy from 1.75 to 1.1 μJ, the pulse duration from 280 to 500 ns for a repetition rate in a range from 40 to 75 kHz and a calculated peak power from 6 to 2 W.

Acknowledgments

This work was supported by Cátedras-CONACyT and CONACyT grant CB-2010–151434.

References

[1] Zhen L 2013 *Laser Phys.* **23** 125105
[2] Cheng X P, Tse C H, Shum P, Wu R F, Tang M, Tan W C and Zhang J 2008 *J. Light. Technol.* **26** 945
[3] Lü X, Han Q, Liu T, Chen Y and Ren K 2014 *Laser Phys.* **24** 115102
[4] Anderson T V, Pérez-Millán P, Keiding S R, Agger S, Duchowicz R and Andrés M V 2006 *Opt. Commun.* **260** 251
[5] Chen N K, Feng Z Z and Liaw S K 2010 *Laser Phys. Lett.* **7** 363
[6] Pérez-Millán P, Díez A, Andrés M V, Zalvidea D and Duchowicz R 2005 *Opt. Express* **13** 5046
[7] Gong M, Peng B, Liu Q and Yan P 2008 *Laser Phys.* **5** 733
[8] Delgado-Pinar M, Zalvidea D, Diez A, Pérez-Millán P and Andrés M V 2006 *Opt. Express* **14** 1106
[9] Yun H-G, Lee S H, Lee M H and Kim K H 2013 *Laser Phys.* **23** 095107
[10] Williams R J, Javanovic N, Marshall G D and Withford M J 2010 *Opt. Express* **18** 7714
[11] Escalante-Zarate L, Barmenkov Y O, Kolpakov S A, Cruz J L and Andrés M V 2012 *Opt. Express* **20** 4397
[12] González-García A, Ibarra Escamilla B, Pottiez O, Kuzin E A, Maya-Ordoñez F, Duran-Sánchez M, Deng C, Haus J W and Powers P E 2013 *Opt. Laser Technol.* **48** 182

[13] Meng Y, Zhang S, Wang X, Du J, Li H, Hao Y and Li X 2012 *Opt. Laser Eng.* **50** 303
[14] Kuznetsov A G and Babin S A 2010 *Laser Phys.* **20** 1266
[15] Zhang S-M, Lu F-Y and Wang J 2007 *Microw. Technol. Lett.* **49** 2183
[16] Kurkov A S, Sadovnikova Y E, Marakulin A V and Sholokhov E M 2010 *Laser Phys. Lett.* **7** 795
[17] Shi W, Petersen E B, Nguyen D T, Yao Z, Chavez-Pirson A, Peyghambarian N and Yu J 2011 *Opt. Lett.* **36** 3575
[18] Li J, Hu T and Jackson S D 2012 *Opt. Lett.* **37** 2208
[19] Ismail M A, Ahmad F, Harun S W, Arof H and Ahmad H 2013 *Laser Phys. Lett.* **10** 025102
[20] Sharma U, Kim C-S and Kang J U 2004 *IEEE Photon. Technol. Lett.* **16** 1277
[21] Duran-Sánchez M, Kuzin E A, Pottiez O, Ibarra-Escamilla B, González-García A, Maya-Ordoñez F, Álvarez-Tamayo R I and Flores-Rosas A 2014 *Laser Phys. Lett.* **11** 015102
[22] Álvarez-Tamayo R I, Durán-Sánchez M, Pottiez O, Kuzin E A, Ibarra-Escamilla B and Flores-Rosas A 2011 *Appl. Opt.* **50** 253