Dual-wavelength all-fiber Q-switched fiber laser using bismuth-doped fiber as saturable absorber

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A passively Q-switched all-fiber laser is demonstrated using a 10-cm-long bismuth-doped fiber (BDF) as a saturable absorber (SA). The dual-wavelength operation was obtained due to the nonlinear effect inside the fabricated BDF, which has a high germanium content. Stable Q-switched pulses were obtained at the dual synchronous wavelengths of 1 530.1 nm and 1 531.1 nm. When the pump power is tuned from 105.3 mW to 191.0 mW, the repetition rate can be varied from 82.6 kMz to 117.6 kHz. The maximum pulse energy and average output power were 83.4 nJ and 9.8 mW, respectively while the minimum pulse width was 8.5 μs at the maximum pump power of 191.0 mW. Our results indicate that BDF could be a promising alternative optical modulator for pulsed fiber laser application.

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Q-switched pulsed fiber laser sources operating at a wavelength of 1.55 μm find extensive applications across diverse fields, such as remote sensing, material processing, optical communication, laser surgery, and defense. Their widespread use is attributed to several key advantages, including high efficiency, exceptional spatial beam quality, compact design, and robustness. This type of laser demonstrates versatility by generating nanosecond or microsecond pulses through the integration of active devices, such as electro-optic or acousto-optic modulators[1,2], and passive saturable absorbers (SAs)[3-5] within the fiber laser cavity.

On the other hand, bismuth-doped fiber (BDF) has also drawn plentiful interest in recent years due to its capability to provide gain for operation in O-band (1 260 nm to 1 360 nm)[6]. This fiber could deliver amplification performance that is comparable to erbium-doped fiber (EDF) and superior to other O-band amplifiers. Therefore, it is very useful for deployment in a future optical communication system to increase the bandwidth capacity. BDFs in silica glass hosts were reported to demonstrate an ultra-broadband emission spanning the O-, E-, S- and U-bands. For instance, RAZDOBREEV et al[7] reported a BDF laser with emission at wavelength region between 1 150 nm and 1 225 nm as it was pumped by a Yb-doped fiber laser (YDFL), and the bismuth concentration of the BDF is 0.005%. It is also reported that the luminescence spectrum of Bi-doped germane-silicate fibers can be extended to 1.7 μm with a deployment of high content (≥50 mol%) of GeO_2 in the BDF[6].

Q-switched fiber lasers could be realized by inserting a doped fiber saturable absorber (DFSA) into a fiber laser cavity[8]. To realize good performance of Q-switched all-fiber laser, a DFSA should have a large absorption cross section compared with the emission cross section of the gain fiber, and its lifetime should also be smaller than the period of laser pulses but greater than the photon lifetime in the cavity. Based on the previously reported result[9], the absorption cross section of BDF at 1.55 μm is estimated to be around 3×10^{-21} cm^2. This value is larger than 0.46×10^{-21} cm^2, the emission cross section of EDF at 1.55 μm[10]. The relaxation process in BDF normally shows a bi-exponential decay[11]. The recovery time typically changes from hundreds of nanoseconds to a few microseconds owing to different fiber core composition[12].

Up to date, many works have been reported on the employment of BDF as SA. Firstly, in 2007, DVOYRIN et al[13] reported a Q-switched YDFL using a BDF SA to generate pulses in a spectral range of 1 050—1 080 nm with a maximum repetition rate of 100 kHz, maximum pulse energy of 100 μJ and minimum pulse width of about 1 μs. However, the BDF had to be placed in a

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separate resonator to build a two-cavity laser scheme, and the length of BDF SA used in the cavity was more than 20 m due to the low absorption of 0.32 dB/m at 1 064 nm. Recently, MUSA et al[14] demonstrated a Q-switched thulium-doped fiber laser (TDFL) operating at 1 967 nm in a typical ring cavity by using BDF SA. The width of the generated pulses changed from 9.04 μs to 6.98 μs with the tuning of repetition rate from 18.1 kHz to 25.22 kHz. Recently, we reported the fabrication of BDF with high content of GeO_2 in the host alumina silica glass and self-starting Q-switched erbium-doped fiber laser (EDFL) based on BDF SA[15]. Even though the BDF has been demonstrated to be an effective DFSA in the EDFL cavity, dual-wavelength Q-switched laser operation has never been reported.

Likewise, dual-wavelength fiber lasers have also gained great attention in recent years owing to their potential application in areas, such as terahertz generation, optical sensors, as well as differential absorption lidars (DIALs) which are utilized explicitly to monitor trace gases. For instance, SHARMA et al[16] have reported that dual-wavelength pulsed laser can be applied to monitor gas by distinguishing the controlled wavelength and the lasing absorption wavelength.

In this paper, we demonstrate a stable dual-wavelength Q-switched EDFL using a 10-cm-long BDF as both SA and nonlinear gain medium. The results indicate the great potential of BDF SA for use in pulse generation especially in 1.53 μm region.

A multi-element-doped bismuth preform is prepared using a combination of the modified chemical vapor deposition (MCVD) process and the solution doping (SD) technique. Subsequently, the preforms underwent appropriate thermal treatment to achieve their desired properties. Different multi-element, such as Al, Ge, P, Ga, Pb and Bi, are incorporated into silica glass serving as core region. Here Ge and P are incorporated via CVD process and other co-dopants, such as Al, Pb, Ga, and Bi, via SD technique through deposition of porous layer. In order to incorporate such co-dopants, the porous germania-phospho-silica layer was deposited inside the silica tube which was soaked with 5% nitric acid water solution of a mixture of suitable strength of dopant precursors, such as $Al(NO_3)_3 \cdot 9H_2O$, $Bi(NO_3)_3 \cdot xH_2O$, $Pb(NO_3)_2$ and $Ga(NO_3)_3 \cdot xH_2O$. The solution soaking process was done for a period of 1 h. The soaked layer was dried at room temperature with flow of an inert N_2 gas after draining out of the solution. All the soaked nitrate precursors are converted to their respective oxides thermally by heating up to ~800 °C with flow of mixture of O_2 and He gases. After proper dehydration process of the soaked porous multi-elements doped layer, all the co-dopants are gradually entered the glass matrix through sintering of the core layer with increasing the heating temperature from 1 400 °C to 1 850 °C. Finally, it converted to a solid rod known as preform through collapsing of the tube with flow of O_2 gases at a high temperature above 2 000 °C. After that, the preform was thermally annealed at 1 100 °C in a controlled heating furnace, creating nanophase separated multi-elements doped particles in core areas of the preform. The final multi-element doped bismuth fiber was drawn from the annealed preform as it was heated above 2 000 °C by a conventional way using a fiber drawing tower. The fiber was designed to be multi-mode with (125±0.5/15±1) μm cladding/core diameters as shown in Fig.1. The numerical aperture (*NA*) of the in-house fabricated BDF has been calculated to be approximately 0.35.

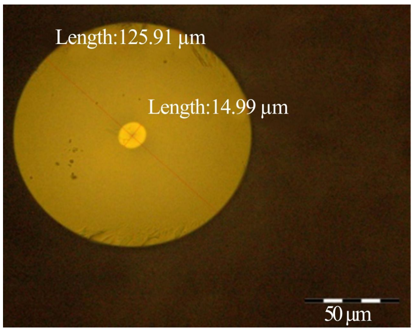

Fig.1 Microscopic cross-sectional view of the fiber (BDF-SA)

Doping levels within the core region of the fiber were quantified using electron-probe micro-analysis (EPMA). The doping level distributions of various co-dopants along the diameter of fiber are shown in Fig.2(a) and (b). The fiber core glass contains a maximum of 0.485 mol% Al_2O_3, 0.076 mol% P_2O_5, 35.51 mol% GeO_2, 0.205 mol% Ga_2O_3, 0.034 mol% PbO and 0.015 2 mol% Bi_2O_3.

The linear absorption of the BDF is then investigated for three different lengths, 10 cm, 30 cm, and 50 cm. It was carried out by transmitting a broadband light from a white light source through the BDF to an optical spectrum analyzer (OSA). Fig.3 shows the measured linear absorption spectra, which indicates that the absorption is much higher at 50 cm compared to that of 10 cm and 30 cm. At 50 cm, the overall absorption is more than 4 dB with two characteristic bands peaking near 980 nm and 1 650 nm. The linear absorption spectra of 10 cm and 30 cm BDFs are almost like each other. Therefore, in this work, we employ 10 cm of BDF to produce dual-wavelength Q-switched fiber laser. At 10 cm, the linear absorption of approximately 0.5 dB is obtained at around 1 550 nm.

The recommended dual-wavelength Q-switched fiber laser design is portrayed in Fig.4. A 1-m-long of EDF with peak absorptions of 23 dB/m and 8 dB/m nominally at 1 530 nm and 980 nm, respectively, is employed as a gain medium. It has core and cladding diameters of 4 μm and 125 μm, respectively with an *NA* of 0.16. A 980 nm laser diode is used to pump the active fiber through a wavelength division multiplexer (WDM) of 980/1 550 nm. It excites erbium ions to create a population inversion in the EDF so that a laser can be realized at 1 530 nm region via a stimulated emission process. A piece of 10 cm BDF was inserted into the ring cavity as the SA. A polarization-insensitive isolator was also added into the cavity to ensure unidirectional light propagation. A 95: 5 coupler was deployed between the SA and WDM to tap out a 5% portion of the propagating signal. This coupling ratio is chosen to reduce cavity loss and allows more photons to oscillate for laser generation. The spectral and temporal laser signal was detected by an OSA and a 1 GHz InGaAs photodetector, respectively. The photodetector was then connected to a digital oscilloscope and radio frequency (RF) spectrum analyzer, to characterize the pulse train in time and frequency domains, respectively. The laser power was measured by an external power meter.

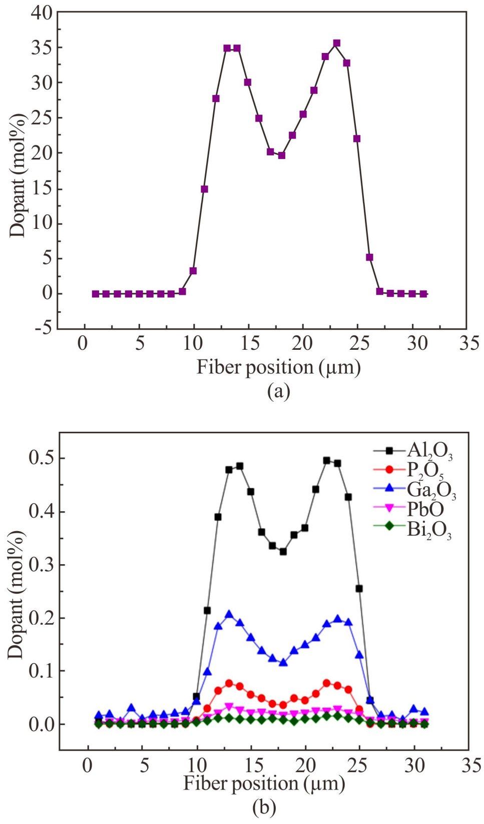

Fig.2 Distribution curves of (a) GeO_2 and (b) other oxide elements, such as Al_2O_3, P_2O_5, Ga_2O_3, PbO, and Bi_2O_3 along the diameter of BDF-SA determined from EPMA

The EDFL started to lase and generated stable Q-switched pulses at a pump power of 105.3 mW. The stable pulses were maintained until the pump power increased to 191.0 mW. As the pump power further increased, the pulse train was diminished, and continuous-wave output was obtained. The spectra of the Q-switched laser in logarithmic scale are shown in Fig.5(a) for two different pump powers, 105.3 mW and 191.0 mW. The output spectrum of a continuous wave laser without the BDF at 105.3 mW is also included in the figure for comparison. As shown in Fig.5(a), dual synchronous wavelengths of 1 530.1 nm and 1 531.1 nm were succeeded during Q-switched operation because of the insertion of the BDF SA. This behavior may be caused by a huge third-order nonlinear effect that is generated by the BDF itself. The operating wavelength of the EDFL is also observed to blue shift from 1 562.2 nm to 1 531 nm region with the incorporation of BDF. This is attributed to cavity loss, which increases with the insertion of BDF due to the absorption and splicing loss. Therefore, the laser operation moves to a shorter wavelength to acquire more gain to compensate for the losses. It is also worthy to note that the operating wavelengths of the Q-switched fiber laser are unchanged with pump power increment.

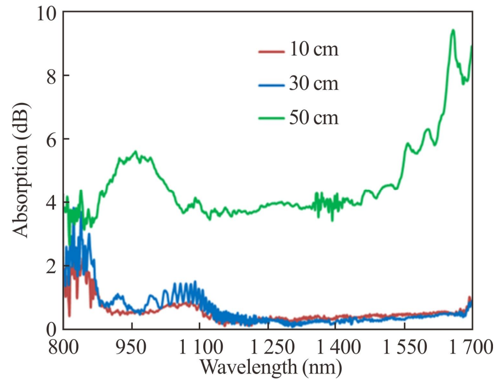

Fig.3 Linear absorption spectra of BDF with different lengths

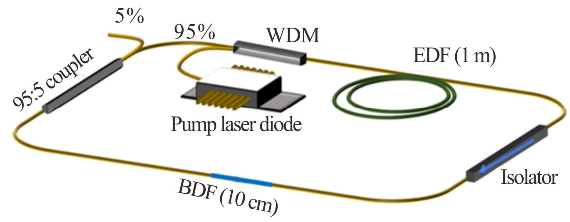

Fig.4 Schematic arrangement of the Q-switched EDFL with BDF SA

The laser pulse train obtained at 191.0 mW pump power is shown in Fig.5(b). The output pulses are stable, and no noticeable intensity fluctuation can be observed. It shows a peak-to-peak separation of 8.5 μs, which is equivalent to 117.6 kHz frequency. Fig.5(c) shows the RF spectrum of output laser at 191.0 mW pump power. It shows a signal to noise ratio (*SNR*) of more than 55 dB at the fundamental frequency of 117.6 kHz. The fundamental frequency obtained is in line with the oscilloscope data. The high *SNR* indicates the stability of the Q-switched pulse. The laser also operated stable in the laboratory condition for 24 h without any noticeable degradation of performance.

Fig.6(a) presents the variation of pulse width and repetition rate at different pump powers. The pulse width decreases from 12.1 μs to 8.5 μs with the ascending pump power from 105.3 mW to 191.0 mW. This is owing to a gain compression that occurs in the laser cavity as the pump power is increased. On the other hand, the pulse repetition rate increases from 82.6 kHz to 117.6 kHz as the pump power is increased within the same regime. This behavior is typical for a Q-switched fiber laser. The optical spectrum was also observed over 48 h under normal laboratory conditions. Neither obvious wavelength shifts nor jitter is occurring during the observation, which indicates that the Q-switched laser performs long-term stability. The gain medium and optical components are fixed onto a metal breadboard to avoid external environmental disturbances. A similar Q-switched performance was also obtained when the experiment was repeated.

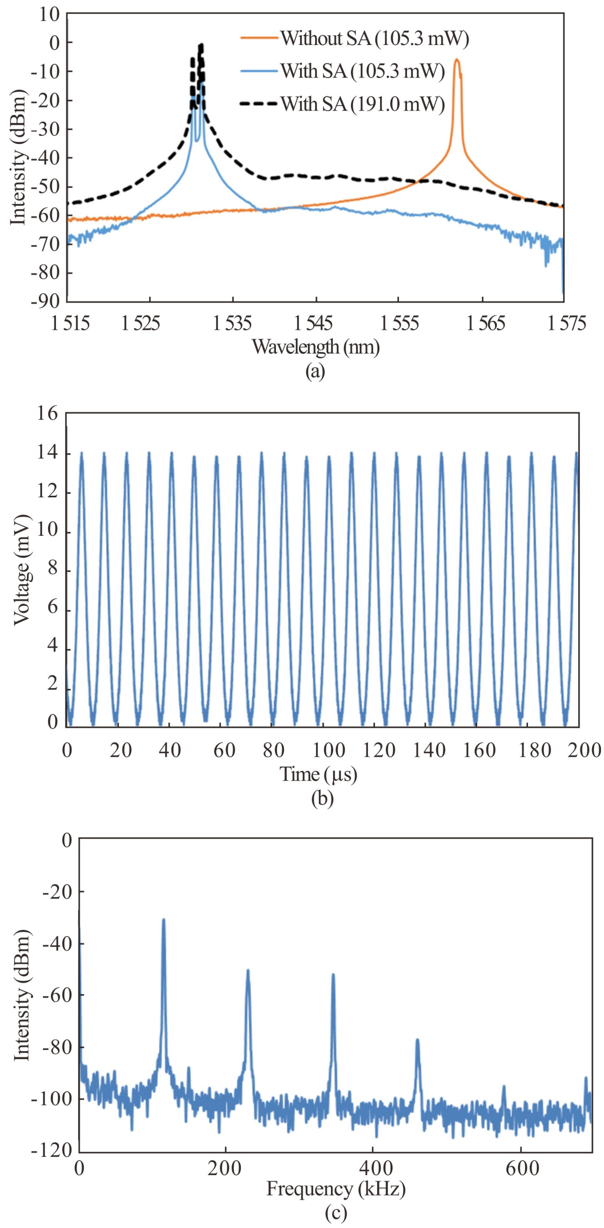

Fig.5 Q-switched laser characteristics: (a) Output spectra; (b) Typical oscilloscope trace; (c) RF spectrum

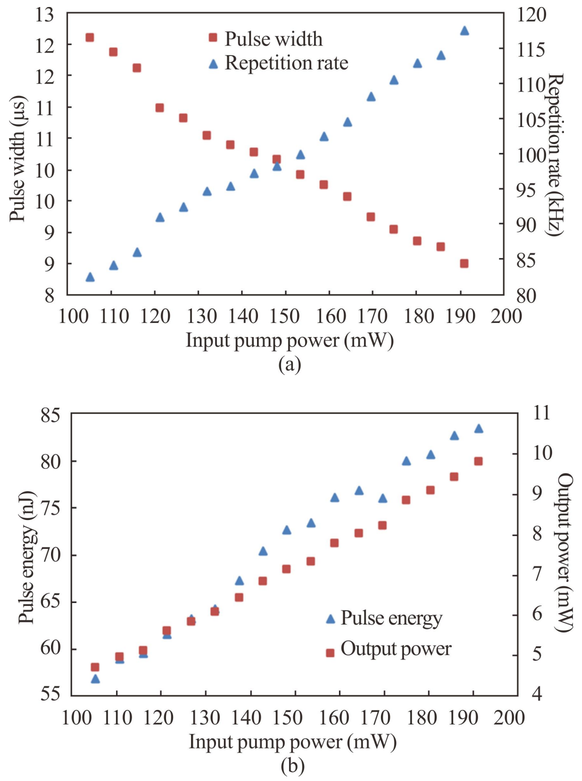

Fig.6 Q-switched laser performance at various launched pump power: (a) Measured pulse width and repetition rate; (b) Pulse energy and average output power

The pulse energy and output power of the Q-switched fiber laser as a function of the pump were plotted in Fig.6(b). Both pulse energy and output power increase with the increment of pump power. At the maximum pump power of 191.0 mW, the pulse energy and output power were recorded at 83.4 nJ and 9.8 mW, respectively. It is worthy to note that a much higher pulse energy is expected to be achieved by using a high-gain fiber such as double-cladding fiber. The minimum pulse width could also be extended to nanosecond regime by reducing the cavity length and optimizing ring cavity design by utilizing optical components with a lower loss. No mode-locked pulse is noticeable even though we have tuned the pump power towards the maximum value in the EDFL cavity. The mode-locked operation could be obtained by extending the cavity length to balance the nonlinearity with the cavity dispersion.

In conclusion, we have succsefully demostrated a stable dual-wavelength Q-switched fiber laser based on a BDF SA. The Q-switched pulses were obtained at the dual synchronous wavelengths of 1 530.1 nm and 1 531.1 nm when the pump power was varied within 105.3 mW to 191.0 mW. When the pump power was ascended within this range, the pulse duration also decreased from 12.1 μs to 8.5 μs while the repetition rate increased from 82.6 kHz to 117.6 kHz. The maximum energy and average output power of the resulting optical pulses were 83.4 nJ and 9.8 mW, respectively. Overall, the Q-switched operation shows good long-term stability, which demonstrates that BDF can be considered as a potential candidate SA material for a robust all-fiber pulse laser system.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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