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Active–passive Q-switched fiber laser based on graphene microfiber

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Abstract

We report an active–passive Q-switched laser based on graphene-covered microfiber modulator. The graphene-covered microfiber not only serves as a passive saturable absorber in a single laser cavity, but also can be used as an all-optical modulation device to synchronize two pulses generated from different wavelengths. The laser can not only actively change the output frequency of the Q-switched pulse to achieve the repetition frequency reduction, but also compress the pulse and increase the peak power of the output pulse. We successfully achieve the output of the active–passive Q-switched pulse using this fiber laser with a repetition rate from 41.1 kHz to 50.5 kHz. The fiber laser has potential applications in simultaneous output of multi-wavelength pulse.

1 Introduction

Q-switching is a technique that converts continuous light into pulses with narrow bandwidth, thereby increasing the light peak power by several orders of magnitude [1]. The laser with Q-switching technology can realize the output of pulsed laser, which can obtain high single-pulse energy and achieve high peak power [2]. It has good application value in medicine, industry, scientific research and military [3–6]. Generally, Q-switching can be divided into passive and active mechanism [7]. The passive one is to use a saturable absorber to realize pulse output. Commonly used saturable absorbers include semiconductor saturable absorbers (SESAMs) [8], single-walled carbon nanotubes (SWCNT) [9, 10], graphene [11–13], and other two-dimensional materials [14]. The passively Q-switched laser has a simple structure and can obtain a narrow pulse width output, but the pulse frequency is very unstable, and it depends on the pump power. It is impossible to change other parameters to adjust the repetition rate at a fixed pump power [15], thus limiting its application. The active Q-switching uses the external drive to adjust the Q factor of the laser to achieve pulse output. The traditional active Q-switching is mainly electro-optic and acousto-optic Q-switching. These types of Q-switching system cannot use the all-fiber structure, and the related devices have higher requirements on alignment and stability, which limits the application [16, 17]. The pulse obtained by the active Q-switching technique has a very stable repetition rate, but the pulse width is not very stable [18, 19]. For Q-switched lasers, the output pulse repetition rate is an important parameter that determines the interaction between the output laser pulse and the target material in practical applications. Therefore, the active and passive Q-switched fiber laser combines the advantages of passive Q-switching and active Q-switching. It can not only obtain narrow pulse width and stable pulse output, but also change the repetition frequency of the output pulse. Moreover, the size of all-fiber laser is smaller than the traditional active Q-switched device, and has lower requirements for application conditions and is easier to integrate into others optical system. Thus, it has wide application opportunities.

Graphene has been a super material in the twenty-first century since it was discovered, which has opened up the research of two-dimensional materials. Graphene enables electron–hole pairs to be generated for any wavelength of light excitation, due to its unique zero bandgap structure. In addition, the graphene are considered to be excellent broadband saturated absorber for its ultra-fast carrier dynamics and extremely high light absorption [20–23]. Microfiber

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with wavelength/sub-wavelength level, which has the advantages of intense evanescent field, intense light field constraint and low loss [24], thus, can be used for highly integrated compact photonic devices to improve device performance.

In this paper, we design an active–passive Q-switched fiber laser based on graphene microfiber (GMF); a Q-switched fiber laser is used to modulate the output pulse. Using this approach, we obtained an active modulation of Q-switched pulse with repetition rate from 41.1 kHz to 50.5 kHz, and synchronously outputting pulses with wavelengths of 1064 nm and 1530 nm, making it potentially attractive in many fields.

2 Experimental arrangement

To fabricate the GMF, a standard single-mode fiber is stripped and the portion of the coating layer is peeled off by flame heating. The bare fiber is then stretched to a microfiber with a length of about 2 cm and a diameter of about 4 µm. A microscopic image is shown in Fig. 1a with a magnification of 1000 times. The GMF is then transferred to the substrate coated with MgF_2 and fixed. Chemical vapor deposition (CVD)-grown graphene is coated on the microfiber by wet transfer method, as shown in Fig. 1b. The thinnest part of the microfiber is uniformly covered by graphene having a length of about 2.96 mm, and the SEM image of this part is shown in Fig. 1c. Raman spectrum of the prepared graphene (Laboratory Ram HR800, excitation wavelength 514 nm) is measured and shown in Fig. 1d. The G peak is the main characteristic peak of graphene, which is related to the in-plane vibration of the sp^2-bonded carbon atoms, and this peak can effectively reflect the number of layers of graphene. The 2D peak, a second-order Raman peak of double phonon resonance, is used to characterize the stacking mode of carbon atoms in graphene samples. The D peak indicates the degree of defect, which generally appears at 1350 cm^{-1}. The intensity ratio of G peak to 2D peak is generally used to judge the number of layers of graphene film [25, 26]. It can be seen that the G peak and the 2D peak of the graphene film are at 1588 cm^{-1} and 2690 cm^{-1}, respectively. While, the D peak is not obvious, indicating that the graphene film has good quality. The intensity ratio of the G peak to the 2D peak is about 0.99, indicating that the graphene is about two layers.

To study whether GMF has optical modulation effect, we designed a simple verification experiment. We pass the continuous wave laser at 980 nm into the chopper to obtain pulsed light at 980 nm. The continuous wave laser at 1530 nm and the pulsed laser at 980 nm are coupled into GMF by a WDM, and then a filter is used to extract the light at 980 nm. The output pulse is observed by an oscilloscope connected with an ultrafast photodetector. Figure 2a is the experimental device diagram. Figure 2b and c are the waveforms of the pulse train of 980 nm and 1530 nm, respectively. It can be seen that the continuous wave light of 1530 nm converts into pulsed light after the modulation

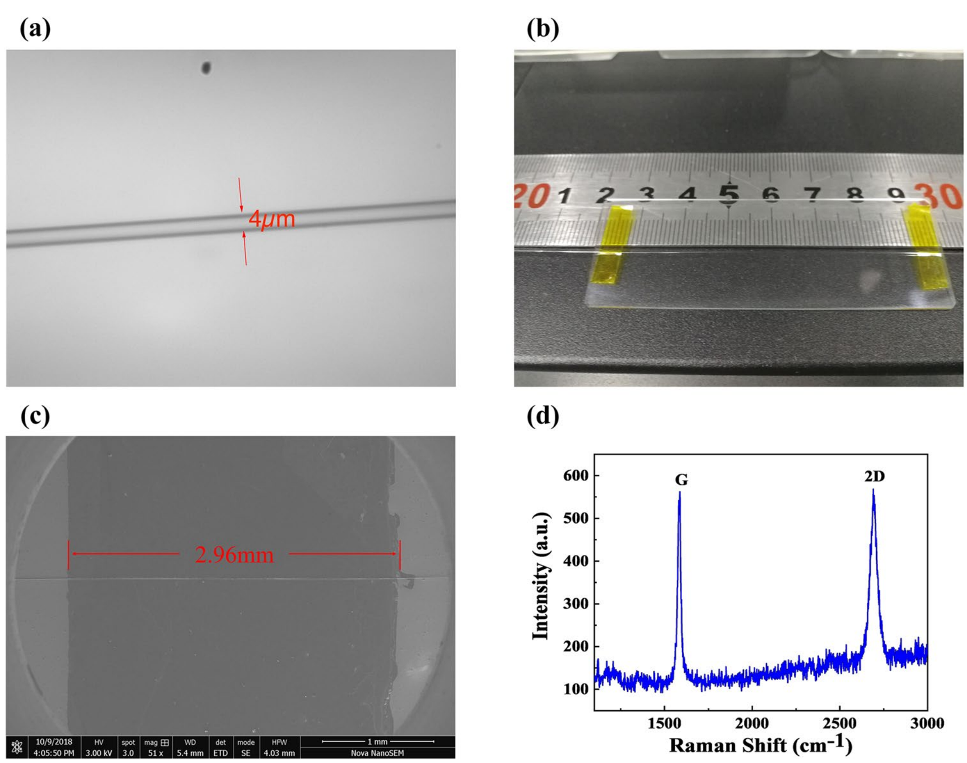

Fig. 1 **a** Microscopy image of the microfiber; **b** GMF transferred to the substrate; **c** SEM of GMF; **d** Raman spectrum of the graphene

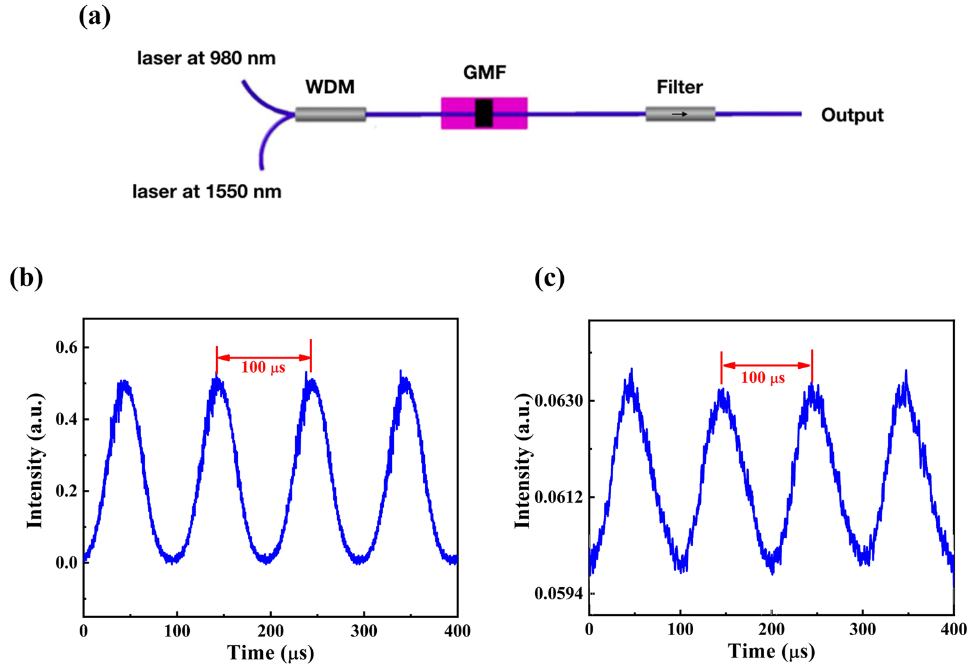

Fig. 2 **a** The verification device used in the experiment; **b** Incident laser waveform with wavelength of 980 nm; **c** output waveform acquired by the oscilloscope

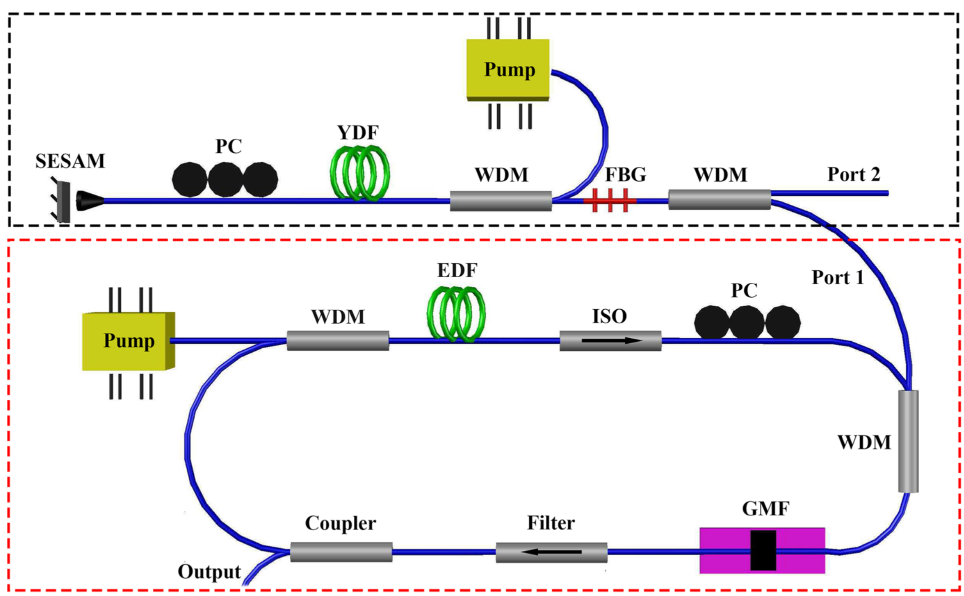

Fig. 3 The setup of the active–passive Q-switched fiber laser

of 980-nm laser. However, we also found that the intense of the output pulse is low.

Based on the above GMF, the output characteristics of active–passive Q-switched laser were studied. The setup of the active–passive Q-switched fiber laser is shown in Fig. 3, which consists of two passively Q-switched fiber lasers with output pulse wavelength at 1060 nm (black frame) and 1530 nm (red frame), respectively. The fiber laser with an operating wavelength of 1060 nm uses a 1.4-m ytterbium-doped fiber as the gain medium, SESAM as the saturable absorber, and a fiber grating (FBG) with a transmittance of 10%. The total cavity length is 15 m. The laser cavity of 1530 nm wavelength uses 1.5-m erbium-doped optical fiber as gain medium, GMF is used as saturable absorber, optical isolator (ISO) is used to ensure the unidirectional light transmission, add a filter with a bandwidth of 1500 nm–1620 nm to ensure that the pulse wavelength at 1060 nm will not affect the detection results, and a 30:70 coupler is used to output the laser. The Q-switched laser is output via the 30% port and measured by an oscilloscope and a spectrometer. The total cavity length of this fiber laser is 15 m. Both fiber lasers are pumped by 980-nm laser diode through WDM.

3 Results and discussion

Firstly, we investigated the laser output performance of two passive Q-switched fiber lasers, respectively. For the 1060 nm laser, when the pump power was set as 80 mW, we adjusted the polarization controller (PC) to obtain steady pulse. The single pulse and corresponding pulse train are shown in Fig. 4a. The pulse interval is 19.61 µs, corresponding to repetition rate of 50.99 kHz. The pulse duration is 2.30 µs. As the same, the passive Q-switched pulse was obtained at 1530 nm when the pump power was 65 mW, as shown in Fig. 4b. The pulse is 20.99 µs, indicating the repetition rate of 47.64 kHz, and pulse duration of 2.46 µs. We can increase the pump power, reduce the total cavity length, or optimize the FBG/OC output ratio to compress the pulse width.

And then, we combined the two lasers to form an active–passive Q-switched configuration. The pump powers of the lasers operating at 1060 nm and 1530 nm were set to 80 mW and 65 mW, respectively, and two PCs were carefully adjusted to obtain stable output pulses. The output pulses were observed with an oscilloscope and a

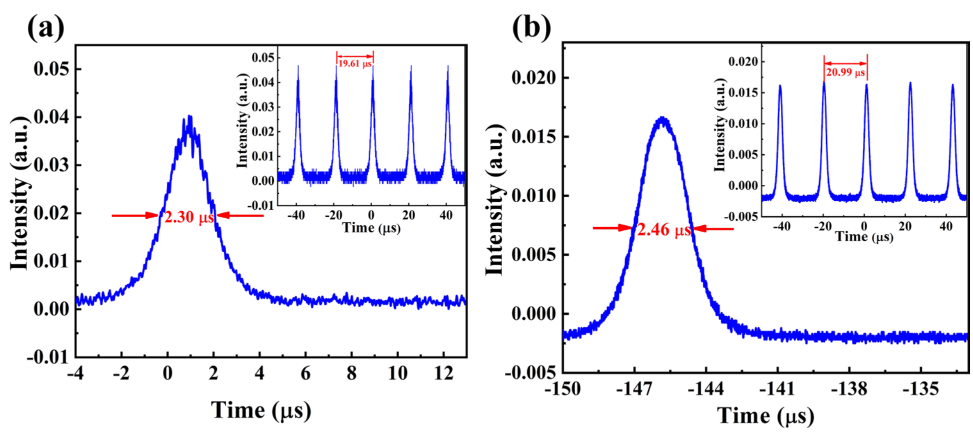

Fig. 4 **a** Sequence with output wavelength of 1060 nm. The pulse-to-pulse interval is 19.61 µs and FWHM of the single sequence is 2.30 µs. **b** Sequence with output wavelength of 1530 nm. The pulse-to-pulse interval is 20.99 µs and FWHM of the single sequence is 2.46 µs

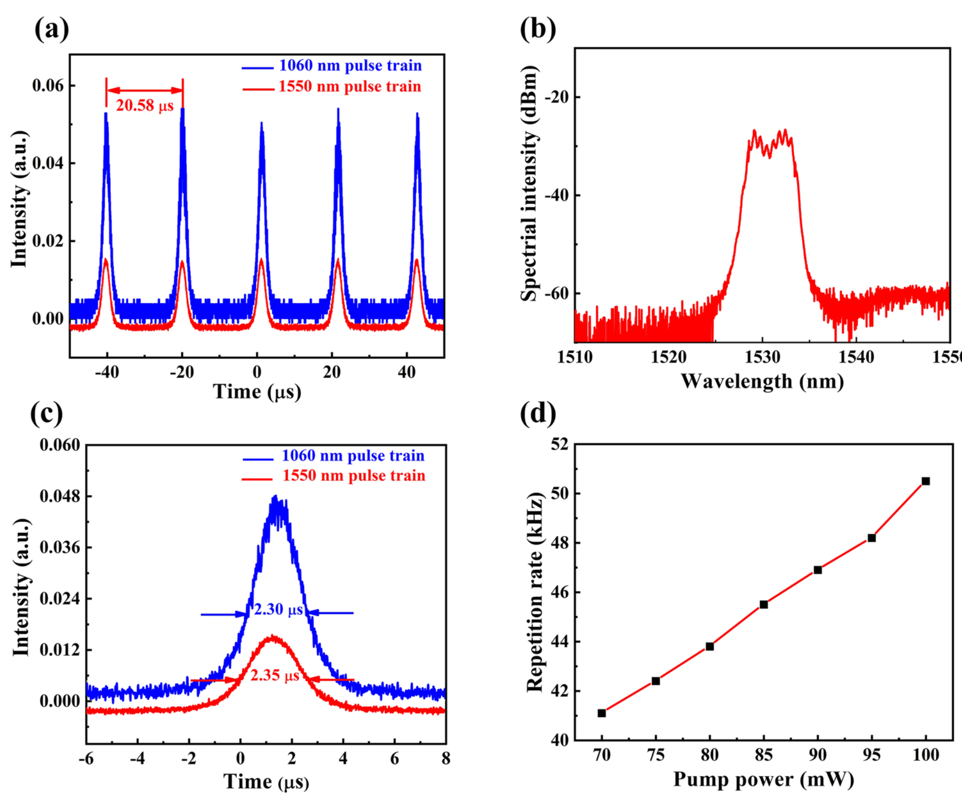

Fig. 5 Active–passive Q-switched operation in fiber laser based on GMF. **a** Output pulse trains; **b** output spectrum; **c** the output time of the two pulses; **d** pulse repetition rate as a function of pump power

spectrometer, respectively, results are shown in Fig. 5a and b. It can be seen that the two pulse trains of the output lasers are synchronized at 48.59-kHz repetition rate. This is slightly less than the repetition rate of the 1060-nm laser when the pump power is 80 mW. The reason is that the repetition rate decreases with a certain loss after fusion in the 1530-nm laser. The central wavelength of the active–passive Q-switched pulse is 1530 nm. There are many longitudinal modes in the Q-switching cavity; the spectrum modulation should be a superposition of different mode frequencies. The sub-peaks in the spectrum correspond to multiple longitudinal modes of continuous oscillation, which may be the multi-longitudinal mode superposition caused by less intense modes competition under low gain conditions [27]. The single pulse result is depicted in Fig. 5c. As can be seen, the pulse duration is 2.30 μs at 1060 nm and 2.35 μs at 1530 nm, respectively. When the modulation light of 1060 nm injects, the graphene starts to absorb the modulated light to reach saturation. Since the absorption of 1530-nm light by graphene is weakened, the light of 1530 nm in the laser cavity is changed from a high loss state to a low loss state, and a pulse output is formed when the pulse of 1060 nm injects. The incidence of modulated light accelerates the formation of 1530-nm pulses. Therefore, comparing with the output pulse of the passively Q-switched laser at 1530 nm, the pulse duration generated by active–passive Q-switched pulse becomes narrower. In addition, it can be found that, if compared with a pulse output from a chopper system with a wavelength of 1530 nm, the output pulse for the chopper system has a lower intensity. This result is similar to that of Liu et al. and Wang et al. [28, 29] The intensity of the modulated light is lower than that of the pumped light, since, after the pulsed laser at 980 nm is absorbed by the graphene, the graphene weakens the absorption of the continuous wave light at 1530 nm, thus generating a pulse with a wavelength of 1530 nm. However, the active–passive Q-switched device forms a resonant cavity and generates a 1530-nm Q-switching pulse; so, the output light intensity is higher. We also study the relationship between the pump power and the repetition rate, as shown in Fig. 5d. Only the pump power of 1060-nm laser was changed. When the pump power increased from 70 mW to 100 mW, the pulse repetition rate increased from 41.1 kHz to 50.5 kHz. As the pump power increases, the pulse builds up more quickly, and the repetition rate increases. Changing the diameter of the microfiber also affects the characteristics of the pulse. The results demonstrate that the evanescent field becomes stronger as the microfiber diameter is reducing. The interaction between light and graphene also enhances when the evanescent field is enlarged [26, 30]. However, the thinner microfiber is more difficult to transfer, and the loss becomes larger. In the experiment, a suitable microfiber needs to be prepared according to the target application.

4 Conclusion

We report an active–passive Q-switched fiber laser to generate synchronous output pulses at dual wavelength. Based on GMF, the active Q-switched pulse was obtained at 1530 nm using the passive Q-switched fiber laser at 1060 nm; the repetition rate of the output pulse varied from 41.1 kHz to 50.5 kHz under the pump power range of 70 mW–100 mW. With the excellent performance of graphene, this fiber laser achieves all-optical operation, compact size and wide operating bandwidth. The GMF device is potential in active–passive Q-switched/mode-locked filed and multi-wavelength synchronous output.

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References

1. P. Petropoulos, H.L. Offerhaus, D.J. Richardson, S. Dhanjal, N.I. Zheludev, Appl. Phys. Lett. **74**(24), 3619–3621 (1999)
2. B. Hitz, Photon. Spectra **41**, 94–95 (2007)
3. U. Sharma, C.S. Kim, J.U. Kang, IEEE Photonics Technol. Lett. **16**(5), 1277–1279 (2004)
4. M. Skorczakowski, J. Swiderski, W. Pichola, P. Nyga, A. Zajac, M. Maciejewska, L. Galecki, J. Kasprzak, S. Gross, A. Heinrich, T. Bragagna, Laser Phys. Lett. **7**(7), 498–504 (2010)
5. X.T. Xu, J.P. Zhai, J.S. Wang, Y.P. Chen, Y.Q. Yu, M. Zhang, I.L. Li, S.C. Ruan, Z.K. Tang, Appl. Phys. Lett. **104**(17), 171107 (2014)
6. M. Xiang, S. Fu, M. Tang, H. Tang, P. Shum, D. Liu, Opt. Express **22**(14), 17448–17457 (2014)
7. B. Chen, X. Zhang, K. Wu, H. Wang, J. Wang, J. Chen, Opt. Express **23**(20), 26723–26737 (2015)
8. S. Kivistö, R. Koskinen, J. Paajaste, S.D. Jackson, M. Guina, O.G. Okhotnikov, Opt. Express **16**(26), 22058–22063 (2008)
9. T. Schibli, K. Minoshima, H. Kataura, E. Itoga, N. Minami, S. Kazaoui, K. Miyashita, M. Tokumoto, Y. Sakakibara, Opt. Express **13**(20), 8025–8803 (2005)
10. A. Martinez, K. Zhou, I. Bennion, S. Yamashita, Opt. Express **18**(11), 11008–11014 (2010)
11. J. Liu, S. Wu, Q.H. Yang, P. Wang, Opt. Lett. **36**(20), 4008–4010 (2011)
12. Z. Luo, M. Zhou, J. Weng, G. Huang, H. Xu, C. Ye, Z. Cai, Opt. Lett. **35**(21), 3709–3711 (2010)
13. Q. Sheng, M. Feng, W. Xin, T. Han, Y. Liu, Z. Liu, J. Tian, Opt. Express **21**(12), 14859–14866 (2013)
14. Z. Luo, M. Liu, A. Luo, W.C. Xu, Chin. Phys. B **27**(9), 094215 (2018)
15. Z. Yu, M. Malmström, O. Tarasenko, W. Margulis, F. Laurell, Opt. Express **18**(11), 11017–11052 (2010)
16. H.H. Kee, G.P. Lees, T.P. Newson, Electron. Lett. **34**(13), 1318 (1998)
17. J.A. Alvarez-Chavez, H.L. Offerhaus, J. Nilsson, P.W. Turner, W.A. Clarkson, D.J. Richardson, Opt. Lett. **25**(1), 37–39 (2000)

18. L. Escalante-Zarate, Y.O. Barmenkov, S.A. Kolpakov, Opt. Express **20**(4), 4397–4402 (2012)
19. L. Li, X. Yang, L. Zhou, W. Xie, Y. Shen, Y. Yang, W. Yang, W. Wang, Z. Lv, X. Duan, M. Chen, Photonics Res. **6**(6), 614–619 (2018)
20. Q. Bao, H. Zhang, Y. Wang, Z. Ni, Y. Yan, Z.X. Shen, K.P. Loh, D.Y. Tang, Adv. Funct. Mater. **19**(19), 3077–3083 (2009)
21. W.B. Cho, J.W. Kim, H.W. Lee, S. Bae, B.H. Hong, S.Y. Choi, I.H. Baek, K. Kim, D.-I. Yeom, F. Rotermund, Opt. Lett. **36**(20), 4089–4091 (2011)
22. M. Zhang, E.J.R. Kelleher, F. Torrisi, Z. Sun, T. Hasan, D. Popa, F. Wang, A.C. Ferrari, S.V. Popov, J.R. Taylor, Opt. Express **20**(22), 25077–25084 (2012)
23. D. Wu, Z. Luo, F. Xiong, C. Zhang, Y. Huang, S. Chen, W. Cai, Z. Cai, H. Xu, IEEE Photonics Technol. Lett. **26**(14), 1474–1477 (2014)
24. W. Li, B. Chen, C. Meng, W. Fang, Y. Xiao, X. Li, Z. Hu, Y. Xu, L. Tong, H. Wang, W. Liu, J. Bao, Y.R. Shen, Nano Lett. **14**(2), 955–959 (2014)
25. Z. Ni, Y. Wang, T. Yu, Z. Shen, Nano Res. **1**(4), 273–291 (2008)
26. J. Wu, H. Xu, J. Zhang, Acta Chim. Sin. **72**(3), 301–318 (2014)
27. Yulong Tang, Xu Jianqiu, Sci. Rep. **5**, 9338 (2015)
28. Z.B. Liu, M. Feng, W.S. Jiang et al., Laser Phys. Lett. **10**(6), 065901 (2013)
29. R. Wang, D. Li, H. Wu et al., IEEE Photonics J. **PP**(99), 1–1 (2017)
30. A. Ren, M. Feng, S. Feng, Y. Ren, S. Yang, Z. Yang, Y. Li, Z. Liu, J. Tian, Opt. Express **23**(16), 21490–21496 (2015)