516 mW, nanosecond Nd:LuAG laser Q-switched by gold nanorods

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Q-switched operation of an Nd:LuAG laser using gold nanorods (GNRs) as the saturable absorber (SA) is reported, which also produces the highest average power among the nanosecond Nd-doped Q-switched lasers by GNRs-based SA. The applied GNRs are prepared using a seed-mediated growth method and then dropped onto the quartz substrate to fabricate the SA. The average power of the Q-switched laser is 516 mW with the shortest pulse duration of 606.7 ns and the repetition rate of 265.1 kHz.

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Solid-state pulsed lasers with ultrashort duration as well as high peak power are effective optical sources widely used in multiple areas, such as medicine, sensing, telecommunications, material processing, and scientific research. Considerable efforts have been devoted to obtain pulses with higher energy, shorter duration, and controllable repetition rate. Ultra-short pulsed have been generated from different Nd-doped lasers such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$, Nd:LGGG, and Nd:LuAG have been utilized in the solid-state pulsed laser systems. Among them, Nd:LuAG is a recently grown one, which is believed to be very promising as the laser active media because of its attractive physical and chemical properties. An Nd:LuAG crystal has a long fluorescence lifetime (277 μs[1]), combined with high thermal conductivity (9.6 W/m · K[2]), and moderate saturation fluence, indicating its potential in obtaining high-energy pulses using techniques such as passively Q-switching. By now, several reports have been presented on Q-switched Nd:LuAG lasers with different saturable absorbers (SAs)[3–8].

As the key element in the passively Q-switching, the SA periodically modulates the Q factor of the laser cavity to achieve the pulsed operation. Therefore, the properties of the SA intensively determine the performance of a pulsed laser, and the demonstration of the novel SA is also of significance besides the gain medium. A semiconductor SA mirror (SESAM) is a successful type of SA that is widely applied in commercial pulsed lasers[9]. However, its drawbacks, such as complex fabrication, narrow operation band, and high costs, limit further investigations[10]. Compared to SESAM, a single-walled carbon nanotube (SWCNT) exhibits several advantages of fast recovery time, low saturation intensity, and high damage threshold[11,12]. Moreover, SWCNT has a broadband operation, and its fabrication is easy with a low cost[12]. In recent years, the research focused on two-dimensional (2D) materials has brought rapid development of the SA family. These materials, including graphene[13,14], topological insulators[15–18], transition metal dichalcogenides[19,20], and black phosphorus[21,22], possess unique electronic and photonic properties and demonstrate distinguished saturable characteristics that are even more advantageous than SWCNT.

More recently, gold nanorods (GNRs), which are the typical metal nanoparticles investigated intensively in biology and medicine, have demonstrated excellent SA performance. This nanomaterial has special third-order nonlinearity as determined by its surface plasmon resonance (SPR)[23]. GNRs normally have two SPR absorption bands defined as the transverse absorption band and the longitudinal absorption band[23]. As to the longitudinal absorption band, the corresponding absorption peak has a flexible location by designing the aspect ratio of GNRs, leading to a wide wavelength range of GNRs-based SA[24]. The fast recovery time of a few picoseconds also contributes to the performance of GNRs as the SA, which will facilitate the ultrashort pulse generation[25]. To date, several reports have been presented on the GNRs Q-switched and mode-locked lasers at a number of wavelengths from the visible band to 2 μm with the pulse duration from femtoseconds to microseconds[26–36], illustrating the effective SA performance of GNRs similar to 2D materials in the generation of a pulsed laser. Among these, a few results have been reported on the

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Nd-doped solid-state lasers. In 2015, Huang *et al.* obtained 4.6-μs-pulses centered at 1064 nm from an Nd:YAG laser using GNRs as the single and combined SA[31]. The highest average power was 740 mW at the pump power of 83 W. In 2016, Zhang *et al.* reported their 396-ns-pulses from a 1064 nm $Nd:YVO_4$ laser Q-switched by the gold nano-bipyramids, and the laser owned the highest repetition rate of 90.6 kHz with the average power of 151 mW at the pump power of 12 W[32]. This group also reported their 1423.4 nm Nd:LGGG laser in 2016 by applying the gold nanobipyramids[33]. The laser output the 514 ns pulse at the repetition rate of 98.6 kHz, and the average power was 125 mW at the pump power of 12.2 W. Song *et al.* reported their GNRs-Q-switched Nd:YAG laser operating at 1064 and 1112 nm, owing the pulse durations of 223 and 504 ns, respectively[34]. The repetition rate was 300 kHz in the 1064 nm laser and 120 kHz in the 1112 nm laser, while the average power was 101 mW at 8.09 W of pump power and 236 mW at 8.57 W, respectively. They also obtained both 1061 and 1106 nm lasers from an $Nd:Gd_3AL_xGa_{(5-x)}O_{12}$ $(x = 0.94)$ (Nd:GAGG) system, and the pulse duration was 250 and 480 ns respectively with the repetition rate of 300 and 100 kHz respectively, with the repetition rate of 300 and 100 kHz, respectively[35]. The average power was 44 mW at the pump power of 7.2 W for 1061 nm and 100 mW for 1106 nm, generating 101 mW average power and using GNRs as the SA. In 2017, Zhang *et al.* reported their 1061 nm Nd, $La:SrF_2$ laser Q-switched by gold nanobipyramids[36]. The pulse of 1.15 μs with the repetition rate of 41 kHz was obtained, and the average power was 92 mW. However, these reports also indicate that the average combined with the low repetition rates below 90.6, 120, and 98.6 kHz, respectively, could not fulfill the demands of application areas. The limitation might be caused by the thermal problem of the GNRs-based SAs applied in the systems or the limitation brought by the gain medium.

In this Letter, a Q-switched Nd:LuAG laser using GNRs as the SA is reported for the first time, to the best of our knowledge. The transmission-type SA was fabricated by applying the seed-mediated growth method together with a simple coating procedure. A pulse duration of 606.7 ns was obtained with the average power as high as 516 mW at the repetition rate of 265.1 kHz. Our work confirmed the great potential of GNRs in the Nd:LuAG laser as the effective SA to generate the nanosecond Q-switched pulse with the average power as high as multi-hundred milliwatts.

The seed-mediated growth method applied to fabricate GNRs has been presented in Ref. [37]. Figure 1 shows the transmission electron microscopy (TEM) images of the GNRs with the scale bars of 100 and 200 nm, in which only a small amount of spherical nanoparticles can be seen. The average aspect ratio of the GNRs was about 6.5, since the GNRs had an average diameter of 12 nm, and the average length was 78 nm. Figure 2 shows the absorption spectrum of the GNRs, having two absorption peaks of 530 and 1080 nm, corresponding to the transverse and longitudinal SPR absorption peaks, respectively. To obtain the transmission-type SA, the solution was first dropped onto the quartz substrate and then dried for 24 h at room temperature. In order to measure the nonlinear optical characteristics of the fabricated SA, the transmission curve corresponding to the incident beam peak intensity was obtained with the technique of a balanced twin detector[38]. The pulsed pump source was a homemade picosecond laser system with the center wavelength of 1064.27 nm. As shown in Fig. 3, the corresponding modulation depth, nonsaturable loss, and saturation intensity were ~13%, ~16%, and ~0.006 MW/cm^2, respectively.

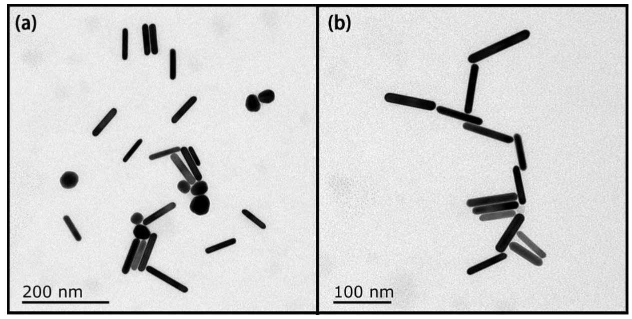

Fig. 1. TEM images of GNRs with the scale bars of (a) 200 and (b) 100 nm.

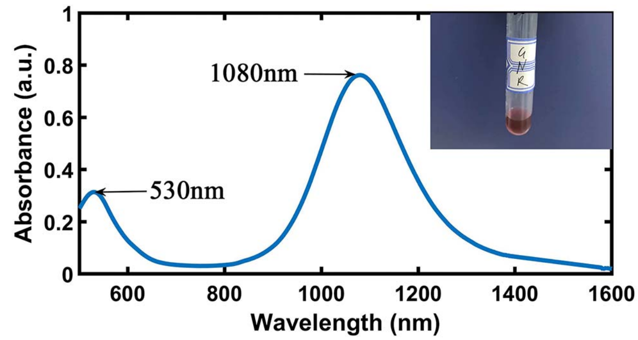

Fig. 2. Absorption spectrum of the GNRs. Inset: photograph of the aqueous solution of GNRs.

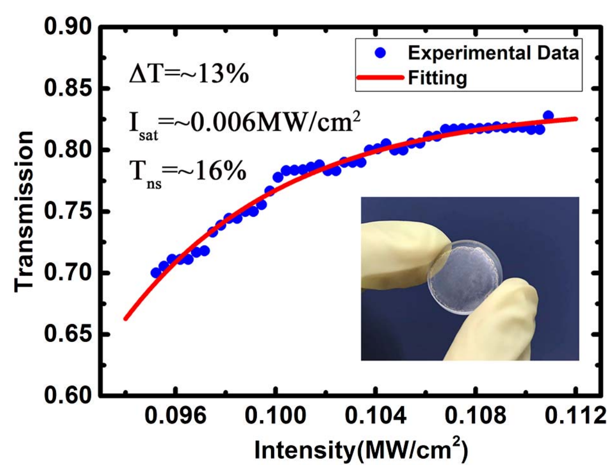

Fig. 3. Nonlinear transmittance of the GNRs-based SA. Inset: photograph of the transmission-type SA.

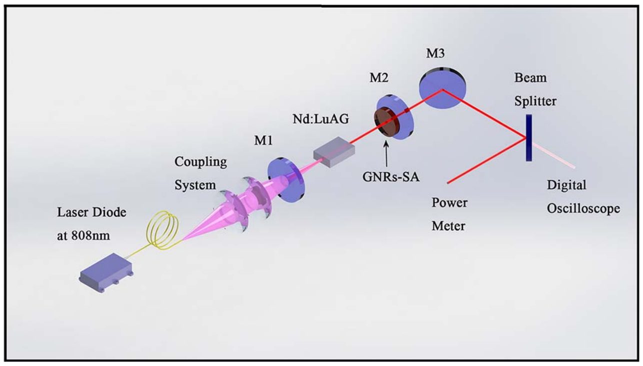

Fig. 4. Experimental setup of the Q-switched Nd:LuAG laser.

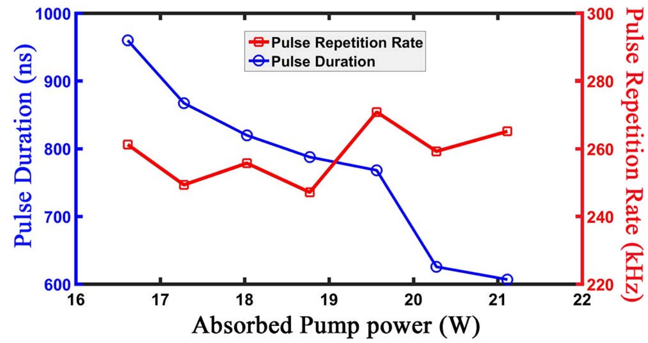

Fig. 5. (Color online) Pulse duration and repetition rate as the function of the absorbed pump power.

Figure 4 shows the setup of the Nd:LuAG laser Q-switched with the GNRs-based SA. The cavity has a linear configuration with the total optical length of 62.45 mm. The Nd:LuAG crystal has the dimensions of 4 mm × 10 mm × 15 mm with the Nd-doped concentration of 0.6 at %. After being wrapped with indium foil, the crystal was mounted on a copper block that was cooled by deionized water at the temperature of 20°C. The two surfaces of the crystal were anti-reflection (AR) coated at both 808 and 1064 nm. The pump source was a fiber-coupled laser diode operating at 808 nm with the fiber core having the numerical aperture of 0.22 and the diameter of 400 μm. The pump light was focused into the crystal by a 1:1 coupling system. M1 was a concave mirror with a curvature radius of 50 mm, AR coated at 808 nm, and high-reflection (HR) coated at 1064 nm. M2 was a plane mirror serving as the output coupler with the transmission of 1.4% at 1064 nm. To precisely measure the output characteristics, a 45° placed dichroic mirror (M3) was used to filter out the residual pump light. The temporal characteristics of the pulse were measured with a 1 GHz digital oscilloscope (Tektronix DPO7104C) connected with a fast photodiode detector owning a rise time of 1ns (Thorlabs Det10A). The spectrum was measured using an optical spectrum analyzer with the resolution of 0.06 nm (Agilent 86140B). The average power was measured by an OPHIR StarLite power meter [OPHIR 50(150)A-BB-26-QUAD].

Before the SA was inserted into the cavity, the continuous wave (CW) operation was realized, and no modulation was observed by the digital oscilloscope. The threshold absorbed pump power of the CW operation was 0.885 W, and the highest average was 5.16 W at the absorbed pump power of 21.11 W. Then, the SA was placed quite closed to M2, and the Q-switched operation was achieved when the absorbed pump power was increased to 16.61 W. The average power was 352 mW with the repetition rate of 261.2 kHz and the pulse duration (FWHM) of 959.8 ns. Figure 5 shows the dependence of pulse duration and pulse repetition rate on the absorbed pump power. The pulse duration reduced as the absorbed pump power increased, while the increasing trend of the repetition rate was not that obvious. This might result from the increased thermal loss of the gain medium and SA[3], and the high intracavity intensity could also attribute to it[35]. However, the average power as well as the calculated single-pulse energy increased almost linearly as the absorbed pump power increased, as shown in Fig. 6. The highest average power was 516 mW together with the shortest pulse duration (FWHM) of 606.7 ns at the absorbed pump power of 21.11 W. The highest pulse energy was 1.95 μJ with the repetition rate of 265.1 kHz. The slope efficiency of the laser system was ~3.8%. Obviously, the low efficiency is mainly due to the loss brought by the SA, since the slope efficiency was as high as ~25% for the CW operation. Figure 7 shows the pulse train at the absorbed power of 21.11 W in the time scale of 10 μs and 400 ns per division (div). The fluctuations of the pulse train might be caused by the heating of the GNRs[31], as well as the instability of the cavity under the high pump power[33]. This could be solved by introducing a cooling device to the SA, and the cavity should be optimized. Figure 8 shows the spectrum of the Q-switched laser, and the central wavelength was located at 1064.68 nm, which was a little different from the CW operation[36]. It should be noted that during the whole Q-switched operation, no thermal damage was observed on the surface of the SA. This indicates that the GNRs-based SA has a good aspect in the practical application.

In conclusion, the passively Q-switched Nd:LuAG laser using GNRs as the SA is demonstrated for the first time, to the best of our knowledge. An average power of 516 mW is obtained at the absorbed pump power of 21.11 W, corresponding to a slope efficiency of ~3.8%, with the

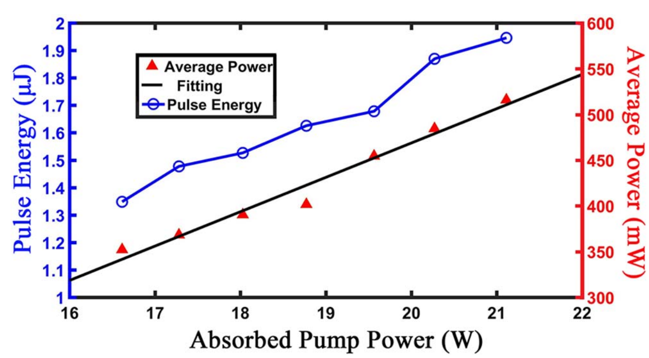

Fig. 6. (Color online) Average power and single-pulse energy as the function of the absorbed pump power.

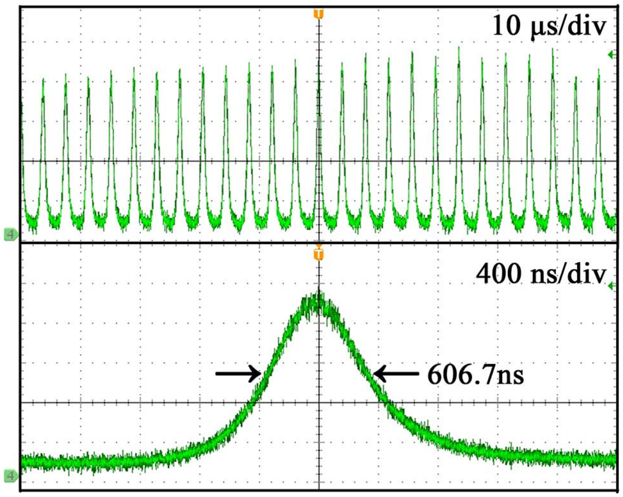

Fig. 7. Pulse train and temporal pulse profile at the absorbed pump power of 21.11 W.

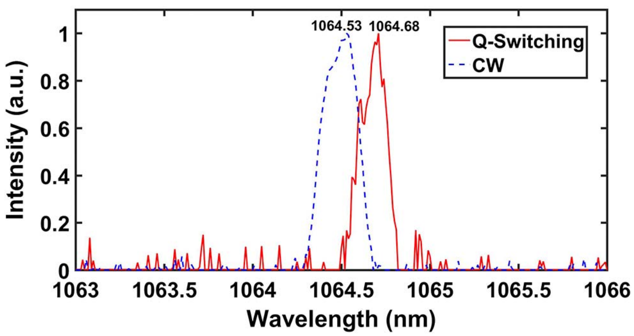

Fig. 8. (Color online) Spectrum of the Q-switched Nd:LuAG laser.

shortest pulse duration of 606.7 ns, the repetition rate of 265.1 kHz, and the corresponding single-pulse energy of 1.95 μJ. Our work represents the highest average power among the reported nanosecond Nd-doped Q-switched lasers by GNRs-based SAs. As the pulse duration is dependent on the modulation depth of SAs, pulsed operation with more practical characteristics is expected with SAs having more optimized nonlinear properties.

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References

1. X. Xu, X. Wang, J. Meng, Y. Cheng, D. Li, S. Cheng, F. Wu, Z. Zhao, and J. Xu, Laser Phys. Lett. **6**, 678 (2009).
2. Y. Kuwano, K. Suda, N. Ishizawa, and T. Yamada, J. Cryst. Growth **260**, 159 (2004).
3. X. T. Chen, S. Z. Zhao, J. Zhao, K. J. Yang, G. Q. Li, D. C. Li, W. C. Qiao, T. Li, H. J. Zhang, T. L. Feng, X. D. Xu, L. H. Zheng, J. Xu, Y. G. Wang, and Y. S. Wang, Opt. Laser Technol. **64**, 7 (2014).
4. J. Q. Di, X. D. Xu, J. Q. Meng, D. Z. Li, D. H. Zhou, F. Wu, and J. Xu, Laser Phys. **21**, 844 (2011).
5. C. Liu, S. Zhao, G. Li, K. Yang, D. Li, T. Li, W. Qiao, T. Feng, X. Chen, X. Xu, L. Zheng, and J. Xu, J. Opt. Soc. Am. B **32**, 1001 (2015).
6. C. Guan, Z. Liu, Z. Cong, Y. Liu, X. Xu, J. Xu, Q. Huang, H. Rao, X. Chen, Y. Zhang, Q. Wu, F. Bai, and S. Zhang, Laser Phys. Lett. **14**, 025003 (2017).
7. L. Chang, S. Z. Zhao, K. J. Yang, J. Zhao, L. H. Zheng, X. D. Xu, J. Q. Di, J. Xu, and Y. G. Wang, Opt. Soc. Am. B **30**, 2710 (2013).
8. J. Zhao, S. Zhao, K. Yang, L. Zheng, and J. Xu, Laser Phys. Lett. **10**, 055806 (2013).
9. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2**, 435 (1996).
10. U. Keller, Nature **424**, 831 (2003).
11. W. B. Cho, J. H. Yim, S. Y. Choi, S. Lee, A. Schmidt, G. Steinmeyer, U. Griebner, V. Petrov, D.-I. Yeom, K. Kim, and F. Rotermund, Adv. Funct. Mater. **20**, 1937 (2010).
12. F. Rotermund, W. B. Cho, S. Y. Choi, I. H. Baek, J. H. Yim, S. Lee, A. Schmidt, G. Steinmeyer, U. Griebner, D.-I. Yeom, K. Kim, and V. Petrov, Quantum Electron. **42**, 663 (2012).
13. W. D. Tan, C. Y. Su, R. J. Knize, G. Q. Xie, L. J. Li, and D. Y. Tang, Appl. Phys. Lett. **96**, 031106 (2010).
14. F. Zhao, Y. Wang, Y. Wang, H. Wang, and Y. Cai, Chin. Opt. Lett. **15**, 101402 (2017).
15. P. Li, G. Zhang, H. Zhang, C. Zhao, J. Chi, Z. Zhao, C. Yang, H. Hu, and Y. Yao, IEEE Photon. Technol. Lett. **26**, 1912 (2014).
16. Z. C. Luo, M. Liu, H. Liu, X. W. Zheng, A. P. Luo, C. J. Zhao, H. Zhang, S. C. Wen, and W. C. Xu, Opt. Lett. **38**, 5212 (2013).
17. B. Xu, Y. Wang, J. Peng, Z. Luo, H. Xu, Z. Cai, and J. Weng, Opt. Express **23**, 7674 (2015).
18. Z. Luo, C. Liu, Y. Huang, D. Wu, J. Wu, H. Xu, Z. Cai, Z. Lin, L. Sun, and J. Weng, IEEE J. Sel. Top. Quant. **20**, 0902708 (2014).
19. B. Lu, L. Yuan, X. Qi, L. Hou, B. Sun, P. Fu, and J. Bai, Chin. Opt. Lett. **14**, 071404 (2016).
20. D. Mao, Y. Wang, C. Ma, L. Han, B. Jiang, X. Gan, S. Hua, W. Zhang, T. Mei, and J. Zhao, Sci. Rep. **5**, 7965 (2015).
21. X. Wang, Z. Wang, Y. Wang, L. Li, G. Yang, and J. Li, Chin. Opt. Lett. **15**, 011402 (2017).
22. J. Ma, S. Lu, Z. Guo, X. Xu, H. Zhang, D. Tang, and D. Fan, Opt. Express **23**, 22643 (2015).
23. I. Cohanoschi, A. Thibert, C. Toro, S. L. Zou, and F. E. Hernandez, Plasmonics **2**, 89 (2007).
24. H. I. Elim, J. Yang, J. Y. Lee, J. Mi, and W. Ji, Appl. Phys. Lett. **88**, 083107 (2006).
25. H. Baida, D. Mongin, D. Christofilos, G. Bachelier, A. Crut, P. Maioli, N. Del Fatti, and F. Vallee, Phys. Rev. Lett. **107**, 057402 (2011).
26. X. Wang, A. Luo, H. Liu, N. Zhao, M. Liu, Y. Zhu, J. Xue, Z. Luo, and W. Xu, Opt. Express **23**, 22602 (2015).
27. Z. Kang, M. Liu, X. Gao, N. Li, S. Yin, G. Qin, and W. Qin, Laser Phys. Lett. **12**, 045105 (2015).
28. S. Wang, Y. Zhang, J. Xing, X. Liu, H. Yu, A. Lieto, M. Tonelli, T. Sum, H. Zhang, and Q. Xiong, Appl. Phys. Lett. **107**, 161103 (2015).
29. D. Wu, J. Peng, Z. Cai, J. Weng, Z. Luo, N. Chen, and H. Xu, Opt. Express **23**, 24071 (2015).
30. H. Huang, M. Li, P. Liu, L. Jin, H. Wang, and D. Shen, Opt. Lett. **41**, 2700 (2016).
31. H. T. Huang, M. Li, L. Wang, X. Liu, D. Y. Shen, and D. Y. Tang, IEEE Photon. J. **7**, 4501210 (2015).
32. H. Zhang and J. Liu, Opt. Lett. **41**, 1150 (2016).
33. H. Zhang, B. Li, and J. Liu, Appl. Opt. **55**, 7351 (2016).

34. T. Song, C. Feng, X. Chen, Q. Wang, G. Qin, W. Qin, X. Gao, Y. Dun, and P. Li, Laser Phys. Lett. **14**, 055808 (2017).
35. C. Feng, M. Liu, Y. Li, X. Gao, Z. Kang, G. Qin, Z. Jia, X. Tao, T. Song, Y. Dun, F. Bai, P. Li, Q. Wang, and J. Fang, Appl. Phys. B **123**, 81 (2017).
36. F. Zhang, H. Zhang, D. Liu, J. Liu, F. Ma, D. Jiang, S. Pang, L. Su, and J. Xu, Chin. Phys. B **26**, 024205 (2017).
37. J. Peng, J. Weng, L. Ren, and L. Sun, IET Nanobiotechnol. **8**, 295 (2014).
38. X. Zheng, R. Chen, G. Shi, J. Zhang, Z. Xu, X. Cheng, and T. Jiang, Opt. Lett. **40**, 3480 (2015).