Beam quality improvement of 1.95-μm GaSb-based broad-area self-pulsed laser by off-axis feedback

Xin Zhang,[a,b] Cunzhu Tong,[a,*] Shili Shu,[a] Yanjing Wang,[a,b] and Lijie Wang[a]

[a]Chinese Academy of Sciences, Changchun Institute of Optics, Fine Mechanics, and Physics, State Key Laboratory of Luminescence and Applications, Changchun, China
[b]University of Chinese Academy of Sciences, Center of Materials Science and Optoelectronics Engineering, Beijing, China

Abstract. It was proposed and demonstrated that a high beam quality self-pulse could be achieved by off-axis feedback for 1.95-μm GaSb-based broad-area laser. The comparative studies of on-axis feedback and off-axis feedback were conducted in an experiment. A highly reflecting (HR) mirror with sharp edge was used in the off-axis feedback system and the overlapping size was changed by moving the HR mirror. At the direct current of 1.8 A, 45-cm external cavity length, and 36% strength of feedback, the off-axis feedback with the overlapping size of 1.2 mm could accomplish the regular periodic pulse with the frequency of 153 MHz. The beam quality M^2 was 12.75 in slow axis and improved nearly doubled compared with that in the on-axis feedback system. © *2020 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.59.7.076112]

Keywords: GaSb-based; self-pulse; high beam quality; mid-infrared.

Paper 20200559 received May 11, 2020; accepted for publication Jul. 8, 2020; published online Jul. 22, 2020.

1 Introduction

In recent years, pulsed lasers with emission wavelengths near 2 μm have been used in many fields, such as remote sensing, medicine, and gas detection.[1–4] At present, the laser emission in 2-μm wavelength regions can be obtained by GaSb-based semiconductor laser, fiber, and solid-state lasers doped with Tm^{3+} and Ho^{3+}.[5–7] The GaSb-based semiconductor lasers possess a number of outstanding properties due to the band-gap engineering of semiconductor gain structures. For example, the emission wavelength of GaSb-based semiconductor laser can be designed from different quantum well structures. It has been demonstrated that the spectral range of GaSb-based semiconductor laser could cover from 1.9 to 3.5 μm operation at room temperature.[8]

Mode-locked and Q-switched are two main modulation technologies to achieve the pulsed laser. But for a diode laser, the periodic pulse could be accomplished by optimizing the feedback strength, external cavity length, and injection current. Compared to other techniques, a diode laser with external feedback requires neither external modulation nor saturable absorbers. Different types of periodic pulse could be achieved by this method.[9–11] In 2003, single-wavelength optical pulses were generated with orthogonal-polarization optical feedback in semiconductor lasers.[12] In 2012, Takeda et al.[13] achieved pulse-package oscillations in broad-area semiconductor lasers subjected to short optical feedback. The spectral properties and temporal dynamics of broad-area diode laser with lateral-mode-selected long-cavity feedback were studied by Chi and Petersen.[14,15] In 2018, Fan et al.'s[16] theory proved the strong optical feedback from short external cavities to achieve ultrashort pulse in semiconductor laser. However, beam quality for the periodic pulse laser caused by external feedback was always ignored. The beam quality of a semiconductor laser, especially for a broad-area waveguide edge emitting laser, is poor in the lateral direction.[17,18] Poor beam quality would seriously influence the application of

*Address all correspondence to Cunzhu Tong, E-mail: tongcz@ciomp.ac.cn

laser, especially for laser communication and fiber coupling. High beam quality of laser can effectively improve transmission distance and coupling efficiency. So determining how to improve the beam quality has always been a focus for semiconductor lasers. A spatial filter is a traditional method to control the beam quality in external cavity for semiconductor laser,[19] but it would lead to the serious loss of emission power.

In this paper, the off-axis feedback method was first applied in GaSb-based broad-area laser (GaSb-BAL) and a high beam quality periodic pulse was achieved in 2-μm region. The beam quality, output power, time traces, and RF signals were compared between on-axis feedback and off-axis feedback.

2 Experiment

Figure 1(a) shows the schematic diagram of on-axis external feedback GaSb-BAL setup in slow-axis direction. The components in the cavity included a GaSb-based broad-area laser, collimation system, tilted output coupler (OC) mirror, lens L2, and gold-coated mirror L3. The external length of cavity was nearly 45 cm. The collimation system consisted of collimation of fast axis and slow axis, respectively. The tilted OC mirror was used to reflect nearly 40% light as output laser by adjusting tilted degrees. So the strength of feedback was $60\% \times 60\% = 36\%$. On the basis of on-axis feedback, a sharp edge HR mirror L1 was used to supply partial feedback with an off-axis reflecting angle α and formed an off-axis feedback GaSb-BAL as shown in Fig. 1(b). α was in the order of several degrees and can be optimized by tuning the angle to obtain the best output performance. When the sharp edge of L1 moved at the edge of beam without any overlapping with laser beam, the overlapping size was recorded as $D = 0$ mm and it was still on-axis feedback. As L1 moved along the direction of the slow axis, the overlapping size was also increased and the off-axis feedback was formed.

3 Results and Discussions

Figure 2 shows the output power of external feedback GaSb-BAL as a function of driving current. The power was measured by thermal power probe (Thorlab314c). Four different overlapping sizes ($D = 0$, $D = 0.4$ mm, $D = 0.8$ mm, and $D = 1.2$ mm) were tried in experiment. With the overlapping size increased, the output power was decreased from 132 to 76 mW at the current of 2 A. There are many lateral modes in GaSb-BAL and these modes could be selected by external feedback. With the overlapping size increased, the more modes would be suppressed so that the output power was decreased. The GaSb-BAL exhibited not only many lateral modes but also an optical spectrum containing a multiplicity of longitudinal. The optical spectrum of

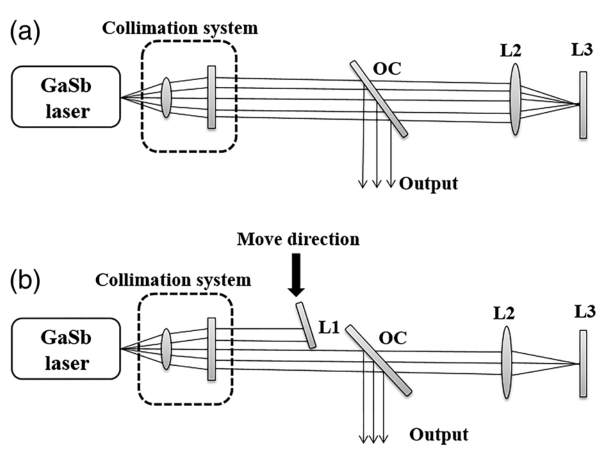

Fig. 1 A schematic diagram of experimental setup for external feedback GaSb-BAL setup. Two feedback methods are illustrated: (a) on-axis feedback and (b) off-axis feedback. L1: sharp edge HR mirror, L2: lens, L3: HR mirror, and OC: output coupler mirror.

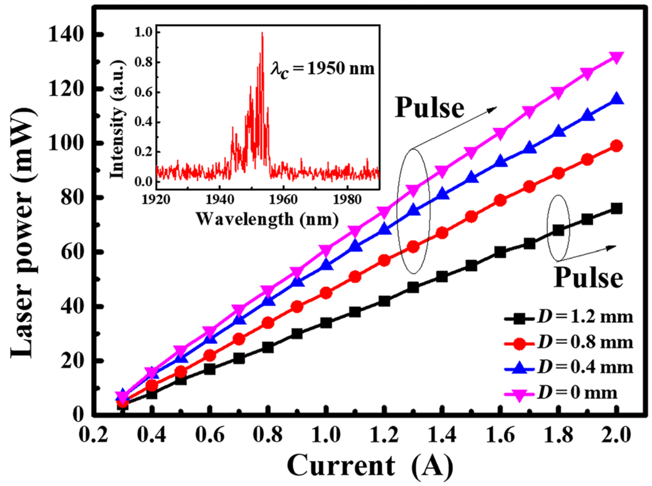

Fig. 2 Average output power of different overlapping sizes ($D = 0$, $D = 0.4$ mm, $D = 0.8$ mm, and $D = 1.2$ mm) GaSb-BAL as a function of driving current. The inset showed the spectra of GaSb-BAL at the current of 1.8 A.

GaSb-BAL was recorded at the current of 1.8 A by a Fourier spectrometer analyzer (Thorlab OSA207C), as shown in the inset of Fig. 2. The center wavelength was 1950 nm.

The time dynamic of GaSb-BAL would also affected by external feedback. In experiment, it was found that the laser changed from stable continuous wave state to unstable oscillation state and then to periodic pulse state with the current increased. It was found that the periodic pulse was started at the current of 1.3 A when the size of overlapping was 0, 0.4 and 0.8 mm. But for 1.2 mm, it was started at 1.8 A. The mechanism of periodic pulse generated was the gain depletion in the laser induced by optical feedback.[20] Under the specific inject current, length of cavity, and feedback strength, when the laser turns on and undergoes the round trip time of external cavity, the successively reflected light is strong enough to deplete the gain below the threshold, thus making the laser temporarily turn off. However, due to the continuous bias current injection, the gain will again increase to the level above the threshold after a short time and the laser will turn on again and then repeat the previous process to generate a train of identical pulses. Figures 3(a) and 3(b) show, respectively, the time traces of GaSb-BAL with on-axis feedback and the off-axis feedback ($D = 1.2$ mm) at the current of 1.8 A. The signal of periodic pulse was captured by a HgCdTe semiconductor detector (PVI-4TE-5, VIGO System) and shown on a 1-GHz bandwidth digital oscilloscope (MDO 3102, Tektronix). It could be observed that the periodic pulse had some fluctuations. Due to the electric pump, even small undulations in the power supply would cause pulse signal fluctuations. The enlarged view of time traces were

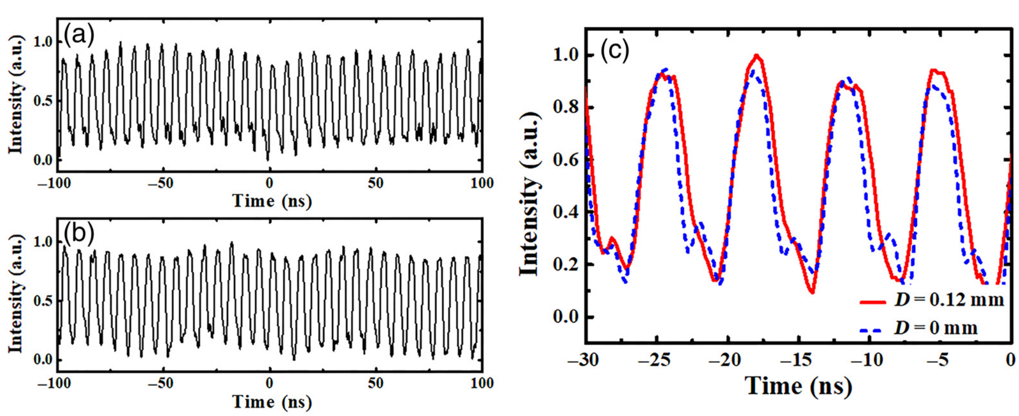

Fig. 3 Time traces of GaSb-BAL at the current of 1.8 A: (a) on-axis feedback, (b) off-axis feedback ($D = 1.2$ mm), and (c) detail pulse profile for these two methods.

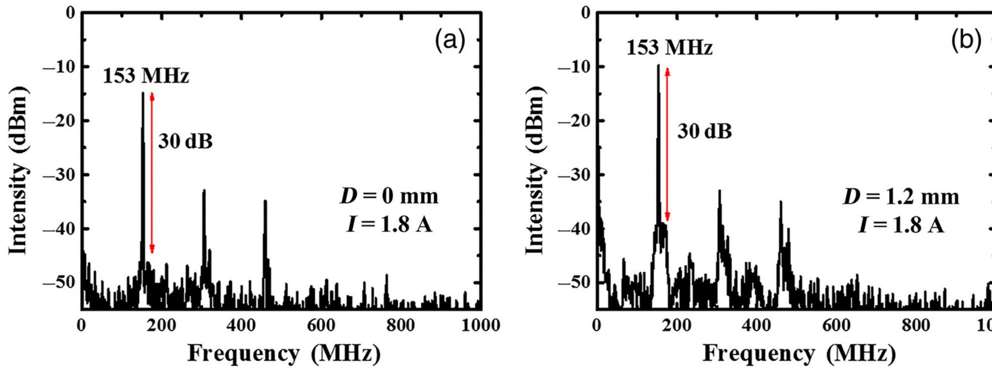

Fig. 4 RF spectrum of GaSb-BAL at the current of 1.8 A: (a) on-axis feedback and (b) off-axis feedback ($D = 1.2$ mm).

also compared, as shown in Fig. 3(c). The pulse width of off-axis feedback was larger than that of on-axis feedback. Under the same OC mirror, the ratio of output power and reflected light should be equal. The output power was decreased by off-axis feedback and the reflected light back to the laser would be also decreased, which would slow down the rate of depleting gain. So the pulse width was broad.

Beside the time domain, the frequency domain was another eventful characteristic for periodic pulse. The RF spectrum of GaSb-BAL was measured, as shown in Fig. 4. The strongest frequency signal for on-axis feedback and off-axis feedback was both 153 MHz with 30 dB SNR. The corresponding period was approximately two times larger than the external cavity round-trip time. However, there were obviously other low-intensity signals near the strongest frequency signal for off-axis feedback. Under this circumstance, the high-order modes were reflected back to the laser by the HR mirror. So the high-order modes would be suppressed. The choice of different modes would change the interaction of light field and carrier in the gain medium of the diode laser,[14] resulting in a change in gain. So that these low-intensity noises may be caused by the suppression of high-order modes.

Under specific external cavity feedback conditions, the off-axis feedback could achieve the similar periodic pulse to on-axis feedback. More importantly, the beam quality could be improved by this method. Beam quality was a very important indicator of laser performance. The detailed beam quality M^2 factor of on-axis and off-axis feedback GaSb-BAL at the current of 2 A were measured and plotted in Fig. 5. The beam width was measured by SPRICON laser beam diagnostics. The measured diameters along the propagation were recorded and fitted to hyperbolic. The M^2 factor was calculated by fitting parameters. The on-axis M^2 factor of slow axis and fast axis were 25.5 and 3.32. And the off-axis M^2 factor of slow axis and fast axis were 12.7 and 3.3.

By this method, the beam quality of off-axis feedback GaSb-BAL as a function of overlapping size at the current of 2 A was measured and shown in Fig. 6(a). It was found that the slow-axis beam quality changed from 25.5 to 12.75 and the fast-axis beam quality almost unchanged when overlapping size changed from 0 to 1.2 mm. Slow-axis beam quality improved nearly doubled at the overlapping size of 1.2 mm. The beam pattern of on-axis feedback was also shown in the inset of Fig. 6(b). The beam size was 4.5 mm in slow-axis direction and 4.8 mm in fast-axis direction. In order to better understand the change of beam profile along the slow axis, it was compared between the on-axis feedback and off-axis feedback as shown in Fig. 6(b). As can be seen, the beam diameter of off-axis feedback was noticeably smaller than that of on-axis feedback in slow axis and some lateral modes were suppressed. So the beam quality was improved by this method. The off-axis feedback could not only effectively improve the beam quality, but also increase in brightness. Beam brightness B was also an important parameter to diode laser, defined by[21]

$$B = \frac{P}{\lambda^2 M_x^2 M_y^2}, \tag{1}$$

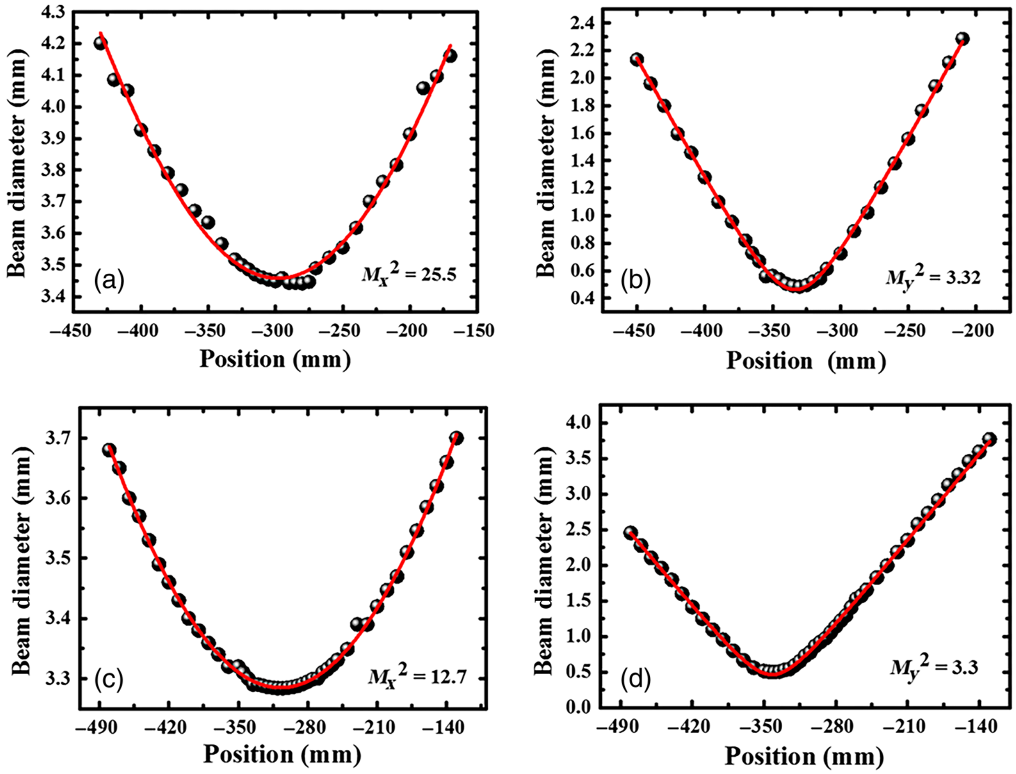

Fig. 5 Beam quality of GaSb-BAL at the current of 2 A: (a) slow-axis (M_x^2) beam quality of on-axis feedback, (b) fast-axis (M_y^2) beam quality of on-axis feedback, (c) slow-axis (M_x^2) beam quality of off-axis feedback ($D = 1.2$ mm), and (d) fast-axis (M_y^2) beam quality of off-axis feedback ($D = 1.2$ mm).

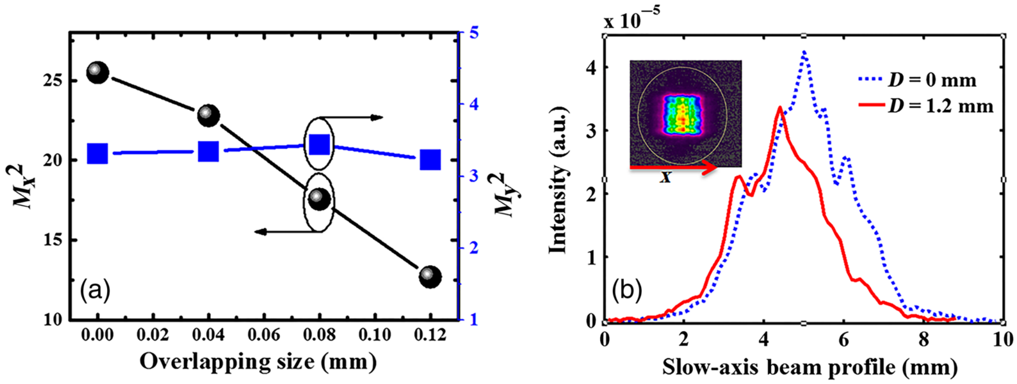

Fig. 6 (a) Beam quality of off-axis feedback GaSb-BAL as a function of overlapping size at the current of 2 A. (b) The beam profile along the slow axis (x direction). The inset showed the beam pattern.

where P is the output power, and λ is the center wavelength. Although the power dropped with changing the overlapping size, the brightness B increased from 41 to 48.5 kW cm^{-2} sr^{-1}.

4 Conclusion

In summary, the off-axis feedback method was used to GaSb-BAL to accomplish the high beam quality periodic pulse. Compared with on-axis feedback method, off-axis feedback could accomplish the similar periodic pulse and the frequency of periodic pulse was 153 MHz with SNR of 30 dB. More importantly, the beam quality has been greatly improved by this method.

The optimum beam qualities of slow axis and fast axis are 12.7 and 3.32 at the current of 2 A. Meanwhile the brightness was also increased and reached peak values in excess of 48.5 $kW\,cm^{-2}\,sr^{-1}$. This work will contribute to the research of external feedback semiconductor laser.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSF) (Nos. 61790584 and 61774153) and the Open Project of Science and Technology on Electro-Optical Information Security Control Laboratory (No. 6142107190309).

References

1. A. Nikitichev and A. I. Stepanov, "2-micrometer lasers for optical monitoring," *J. Opt. Technol.* **66**, 718–723 (1999).
2. G. Sobon et al., "All-polarization maintaining, graphene-based femtosecond Tm-doped all-fiber laser," *Opt. Express* **23**(7), 9339–9346 (2015).
3. W. Wei et al., "Passively Q-switched operation of a Tm, Ho:$LuVO_4$ laser with a graphene saturable absorber," *Appl. Sci.* **8**(6), 954 (2018).
4. B. J. Perrett and P. D. Mason, "Modelling of thermal effects within a 2-μm pumped ZGP optical parametric oscillator operating in the mid-infrared," *Proc. SPIE* **5260**, 264–274 (2004).
5. S. Husaini and R. G. Bedford, "Graphene saturable absorber for high power semiconductor disk laser mode-locking," *Appl. Phys. Lett.* **104**(16), 161107 (2014).
6. C. Jin, D. Li, and Y. Bai, "Wideband tunable graphene-based passively Q-switched Tm:YAPlaser," *Laser Phys.* **25**(4), 045802 (2015).
7. W. Yicheng, C. Weidong, and M. Mark, "Sub-100 fs Tm:$MgWO_4$ laser at 2017 nm mode locked by a graphene saturable absorber," *Opt. Lett.* **42**(16), 3076 (2017).
8. S. Shu, G. Hou, and J. Feng, "Progress of optically pumped GaSb based semiconductor disk laser," *Opto-Electron. Adv.* **1**, 170003 (2018).
9. Z. P. Su, Z. C. Ji, and Z. W. Zhu, "Phase locking of laser diode array by using an off-axis external Talbot cavity," *Chin. Phys. Lett.* **29**(5), 054210 (2012).
10. T. Tachikawa, S. Takimoto, and R. Shogenji, "Dynamics of broad-area semiconductor lasers with short optical feedback," *IEEE J. Quantum Electron.* **46**(2), 140–149 (2010).
11. A. Pimenov, V. Z. Tronciu, and U. Bandelow, "Dynamical regimes of a multistripe laser array with external off-axis feedback," *J. Opt. Soc. Am. B* **30**(6), 1606 (2013).
12. S. K. Mandre, I. Fischer, and E. Wolfgand, "Spatiotemporal emission dynamics of a broad-area semiconductor laser in an external cavity: stabilization and feedback-induced instabilities," *Opt. Commun.* **244**(1–6), 355–365 (2005).
13. A. Takeda, R. Shogenji, and J. Ohtsubo, "Dynamics and pulse-package oscillations in broad-area semiconductor lasers with short optical feedback," *Appl. Phys. Lett.* **101**(23), 231105 (2012).
14. M. Chi and P. M. Petersen, "Dynamics of a broad-area diode laser with lateral-mode-selected long-cavity feedback," *J. Appl. Phys.* **116**(10), 103101 (2014).
15. M. Chi and P. M. Petersen, "Spectral properties of a broad-area diode laser with off-axis external-cavity feedback," *Appl. Phys. Lett.* **103**(17), 171112 (2013).
16. Y. Fan, K. A. Shore, and Y. Hong, "Ultrashort pulse generation in a semiconductor laser with strong coherent optical feedback," *IET Optoelectron.* **13**(1), 36–39 (2019).
17. Z. Lu, L. Wang, and Y. Zhang, "High-power GaSb-based microstripe broad-area lasers," *Appl. Phys. Express* **11**(3), 032702 (2018).
18. V. Raab and R. Menzel, "External resonator design for high-power laser diodes that yields 400 mW of TEM(00) power," *Opt. Lett.* **27**(3), 167–169 (2002).
19. D. Vijayakumar, O. B. Jensen, and B. Thestrup, "980 nm high brightness external cavity broad area diode laser bar," *Opt. Express* **17**(7), 5684–5690 (2009).
20. J. Ohtsubo et al., *Semiconductor Lasers: Stability Instability and Chaos*, Springer-Verlag, Berlin, Heideberg (2013).

21. R. Diehl et al., *High-Power Diode Lasers: Fundamentals, Technology, Applications*, Springer-Verlag, Berlin, Heideberg (2000).

Xin Zhang received his MSc degree in optics from the University of Chinese Academy of Sciences in 2017. Since 2017, he has been employed at Changchun Institute of Optics, Fine Mechanics and Physics, as a laser engineer/PhD student, where he is concerned with topics in the fields of mid-infrared pulsed laser, including the fiber laser and semiconductor laser.

Biographies of the other authors are not available.