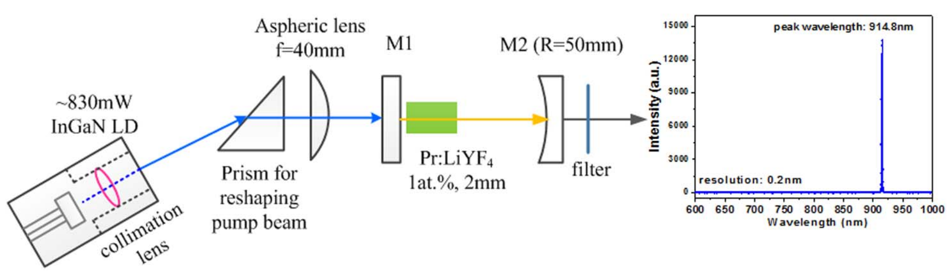
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

InGaN-LD-Pumped $Pr^{3+}:LiYF_4$ Continuous-Wave Laser at 915 nm

Volume 6, Number 6, December 2014

Biao Qu
Bin Xu
Yongjie Cheng
Saiyu Luo
Huiying Xu
Yikun Bu
Patrice Camy
Jean-Louis Doualan
Richard Moncorgé
Zhiping Cai



DOI: 10.1109/JPHOT.2014.2374618

InGaN-LD-Pumped Pr^{3+}:$LiYF_4$ Continuous-Wave Laser at 915 nm

Biao Qu,[1] Bin Xu,[1] Yongjie Cheng,[1] Saiyu Luo,[1] Huiying Xu,[1] Yikun Bu,[1] Patrice Camy,[2] Jean-Louis Doualan,[2] Richard Moncorgé,[2] and Zhiping Cai[1]

[1]Department of Electronic Engineering, Xiamen University, Xiamen 361005, China
[2]Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA-CNRS-ENSICaen, Université de Caen, 14050 Caen, France

DOI: 10.1109/JPHOT.2014.2374618

Manuscript received October 30, 2014; accepted November 10, 2014. Date of current version December 16, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 61275050; by the Specialized Research Fund for the Doctoral Program of Higher Education under Grant 20120121110034 and Grant 20130121120043; by the Fundamental Research Funds for the Central Universities under Grant 2013121022; by the Natural Science Foundation of Fujian Province of China under Grant 2014J01251; by the Scientific Research Foundation for Returned Scholars, Ministry of Education of China; and by the Xiamen Science and Technologic Project under Grant 3502Z20113004. Corresponding author: Z. Cai (e-mail: zpcai@xmu.edu.cn).

Abstract: We demonstrate the first InGaN-LD-pumped room temperature and continuous-wave laser operation of a Pr^{3+}:$LiYF_4$ crystal at 915 nm. A maximum output power up to 78 mW with a laser slope efficiency of about 17% is obtained. The round-trip optical losses are estimated to be about 0.45%, and the M^2 beam quality factors measured in x and y dimensions are about 1.07 and 1.04, respectively.

Index Terms: Solid state lasers, diode-pumped lasers, infrared lasers.

1. Introduction

In the past decade, the fluoride crystals doped with trivalent Praseodymium ions, i.e., Pr^{3+}:$LiYF_4$, have drawn great attentions of researchers owing to the capability of lasing in several visible regions by directly transitions [1]–[11]. Correspondingly, three kinds of pumping source are developed according to the three peak absorptions, i.e., InGaN LDs at ~444 nm [3]–[8], DPSSLs at ~469 nm [9], [10], and OPSLs at ~479 nm [12]. Compared to the complicated configurations and high cost of OPSLs and DPSSLs, InGaN LDs are compact and cheap, and furthermore, the output power is scaled rapidly to watts in recent years, which is also commercially available. However, up to now, the InGaN-pumped Pr^{3+}:$LiYF_4$ lasers were mainly operated at green (522.5 nm and 545.9 nm: $^3P_1 + {}^1I_6 \rightarrow {}^3H_5$ emission transition) [5], orange (607 nm: $^3P_0 \rightarrow {}^3H_6$) [5], [7], red (640 nm: $^3P_0 \rightarrow {}^3F_2$) [5], [9] and deep red (698 nm: $^3P_0 \rightarrow {}^3F_3$ and 720 nm: $^3P_0 \rightarrow {}^3F_4$) [6], [8] laser wavelengths, thus within the visible spectral domain. Very few results can be found in the literature in the near-infrared. The only significant one was reported by Sandrock *et al.* [1] in 1994, thus nearly twenty years ago, who operated a Pr^{3+}:$LiYF_4$ laser at a laser wavelength of 907 nm ($^3P_0 \rightarrow {}^1G_4$ emission transition) with a maximum output power of 23 mW by pumping the crystal with an argon-ion laser tuned at 457.9 nm.

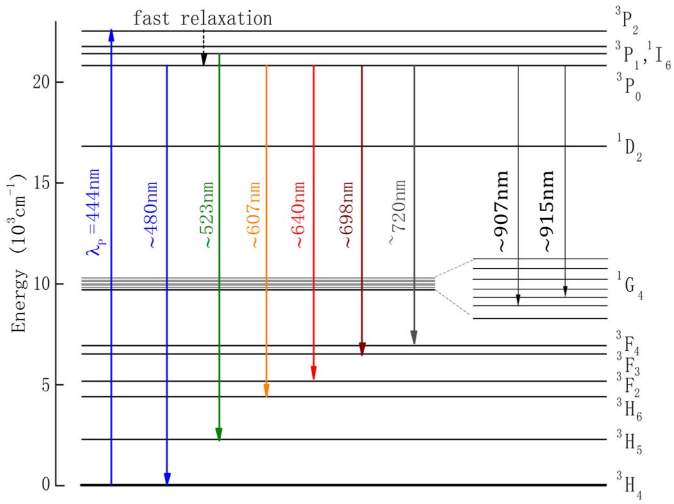


Fig. 1. Energy levels and laser transitions observed in Pr^{3+}:$LiYF_4$.

In this letter, we focus and report on the laser operation of an InGaN laser diode pumped Pr^{3+}:$LiYF_4$ crystal at a near infrared laser wavelength of 915 nm. It is thus obtained a maximum output power of 78 mW with slope and optical-to-optical efficiencies up to about 17% and 14%, respectively. Such a diode-pumped 915 nm laser source seems to be more favorable than the 980 nm laser diodes currently used in some bio-imaging techniques [12], because of reduced heat production and lower water absorption in biological species, and also because it can be used as a laser source for optical tweezers [13] in biomedical technology.

2. Stark Energy Levels and Infrared Fluorescence

Fig. 1 shows the energy levels and the main laser transitions observed in Pr^{3+}:$LiYF_4$ [14]. This energy level diagram clearly indicates that visible emissions exclusively occur from the ^3P_J and $^1I_6$ thermalized multiplets down to the ^3H_J and ^3F_J terminal levels. On the other hand, the near infrared emission transitions occurring around 910 nm only results from transitions between the same upper metastable level $^3P_0$ down to several Stark sub-levels of the $^1G_4$ multiplet, this multiplet being split, according to the tetragonal local site symmetry of the Pr^{3+} ions inside the $LiYF_4$ crystal, into 7 Stark sub-levels. Moreover, the most intense one located around 907 and 915 nm correspond to adjacent $^1G_4$ Stark sub-levels with an energy gap of about 100 cm^{-1} [14].

The polarization-dependent fluorescence spectra of Pr^{3+}:$LiYF_4$ excited by an InGaN laser diode (LD) emitting at about 444 nm and calibrated in unit of cross sections are reported in Fig. 2. According to these spectra, the main emission peak occurs at 914.8 nm in π polarization with a stimulated emission cross section of about 3.7×10^{-20} cm^2, while that found around 907.0 nm occurs in σ polarization with a stimulated emission cross section of about 1.5×10^{-20} cm^2. Therefore, the peak at 914.8 nm occurs with a stimulated emission cross section which is nearly 2.5 times larger than the other one. Besides these two intense emission lines, five other peaks around 896 nm, 923 nm, 930 nm, 939 nm, and 974 nm can be also observed. All of them, like those located around 907 and 914.8 nm, are associated to emission transitions from the $^3P_0$ emitting state to the seven Stark sub-levels of the $^1G_4$ multiplet. The $^3P_0$ emitting state being located around 20 870 cm^{-1}, it is possible to position these different Stark sub-levels at 9718 cm^{-1}, 9845 cm^{-1}, 9939 cm^{-1}, 10 036 cm^{-1}, 10 117 cm^{-1}, 10 217 cm^{-1}, and 10 603 cm^{-1}, in good agreement with the energy level positions derived in [14], except for the latter which was wrongly estimated around 10313 cm^{-1}.

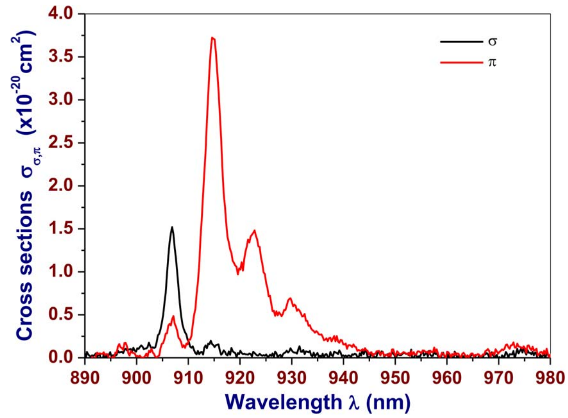


Fig. 2. Polarized emission cross section spectra of Pr^{3+}:$LiYF_4$ registered between 890 and 980 nm after excitation with a blue InGaN laser diode at 444 nm.

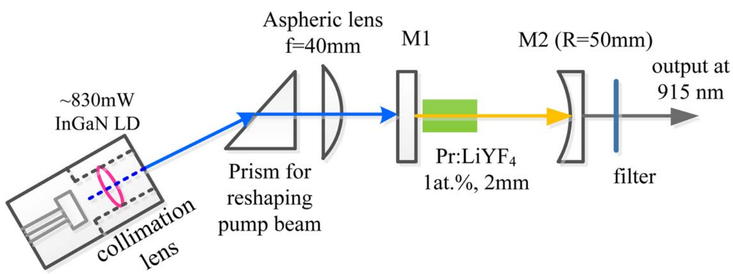


Fig. 3. Schematic of the InGaN-LD-pumped Pr^{3+}:$LiYF_4$ laser at 915 nm.

3. Laser Experimental Set-Up

The laser experimental set-up is sketched in Fig. 3. The pumping source is a linearly polarized InGaN LD with a maximum output power of ~830 mW. The peak wavelength is at 443.8 nm with a line-width of 1.7 nm (FWHM) at full power. In order to optimize the pump beam quality, a simple isocele right-angle prism with high transmission coatings at the pump wavelength was employed for beam reshaping. The pumping beam was focused onto the Pr^{3+}:$LiYF_4$ crystal with an aspheric lens having a focal length of 40 mm, which leads to a pumping spot size of 72 μm. The 2 mm long 1at% Pr^{3+}:$LiYF_4$ laser crystal is a-cut which allows the emission in the π polarization and σ polarization. The crystal had uncoated, flat, parallel and polished end-faces and was only mounted onto a copper plate without any additional cooling. The polarization of the pumping source is oriented along the c-axis of the crystal in longitudinal direction, which is perpendicular to the direction of beam propagation. The crystal absorbed around 70% of the pump power. The laser cavity was a simple plano-concave cavity with an optimized physical length of around 48 mm for an output coupler (OC) having a 50 mm radius of curvature. In order to achieve the expected near infrared laser emission, particular attention was paid on the suppression of the stronger emission located in the visible region, which could be realized by using appropriate mirrors. The flat dichroic input mirror M1 had a transmission of 87.2% at the 444 nm pump wavelength and a reflection exceeding 99.9% at the 915 nm emission. Four curved output mirrors (M2) were utilized, all with the radius of curvature of 50 mm and different transmissions of 0.05%, 0.5%, 0.8%, and 1.5% at 915 nm.

4. Results and Discussion

Fig. 4 shows the laser performance of our LD-pumped Pr^{3+}:$LiYF_4$ laser at 915 nm as obtained by using the four different OCs. With the 0.05% OC, the one was primarily used to get laser

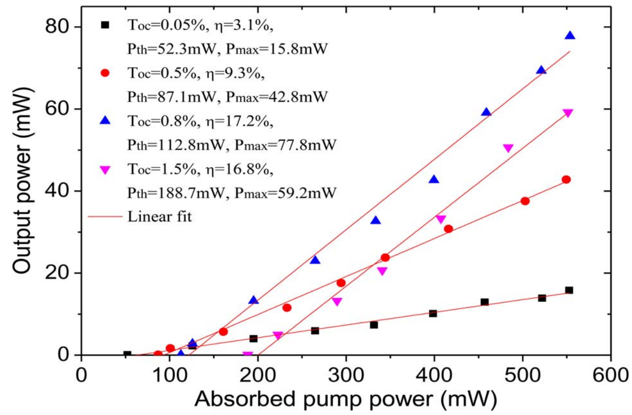


Fig. 4. Laser output versus absorbed pump power curves of an InGaN-LD-pumped Pr^{3+}:$LiYF_4$ laser crystal at 915 nm.

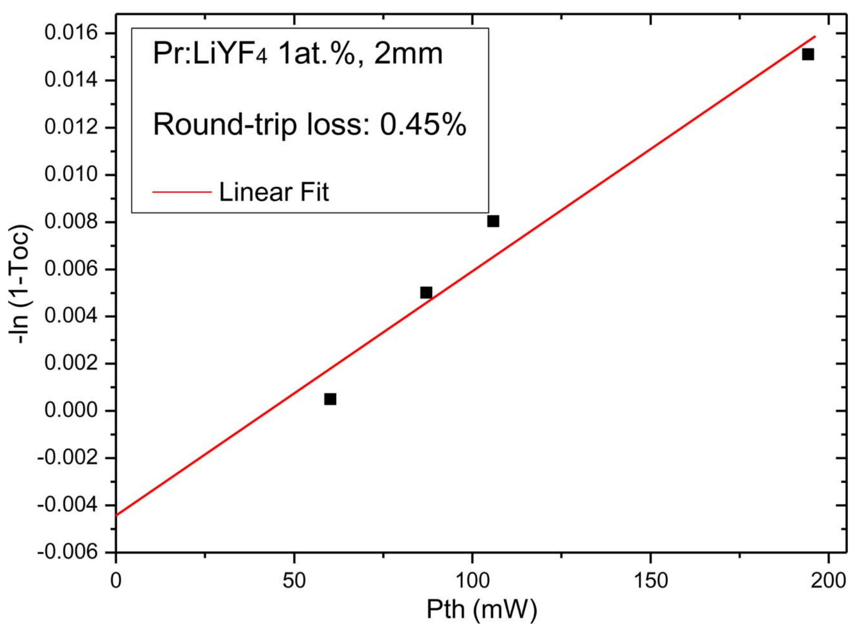


Fig. 5. Findlay-Clay plot for the 915 nm laser cavity.

action more easily, laser threshold was reached for an absorbed pump power of about 52.3 mW, and a maximum output power of about 15.8 mW was achieved leading to a laser slope efficiency of 3.1% with respect to the absorbed pump power. For the other OCs with 0.5%, 0.8%, and 1.5% transmissions, the laser threshold increases regularly, as expected, up to about 188.7 mW. This is not quite the case, however, for the laser slope efficiency. Indeed, it increases up to a maximum value of about 17.2% giving a maximum output power of about 78 mW for an OC transmission of 0.8%, but then it saturates (and eventually decreases) with a value of about 16.8% for the 1.5% transmission OC. It is also worth noting that the achieved 915 nm laser emission was strictly π polarized, as the pump light, and that no 907 nm laser emission could be detected.

The complete experimental data allow an estimation of the round-trip cavity losses by using the Findlay-Clay method, the one is based on the variation of the laser threshold P_{th} with the output mirror transmission T. According to the plot reported in Fig. 5, it is found round-trip cavity losses of about 0.45%.

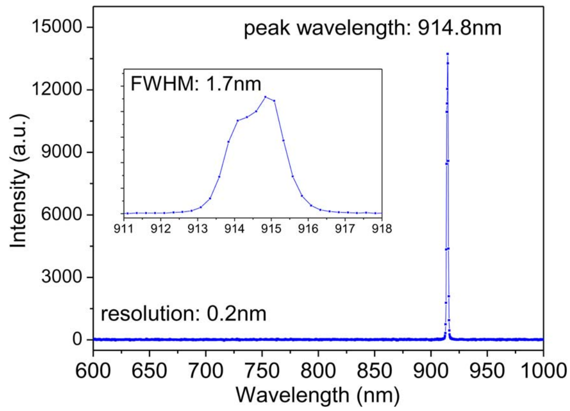


Fig. 6. Infrared laser emission at ~915 nm measured by using "Ocean Optics HR4000" optical spectrum analyzer (OSA) with resolution of 0.2 nm.

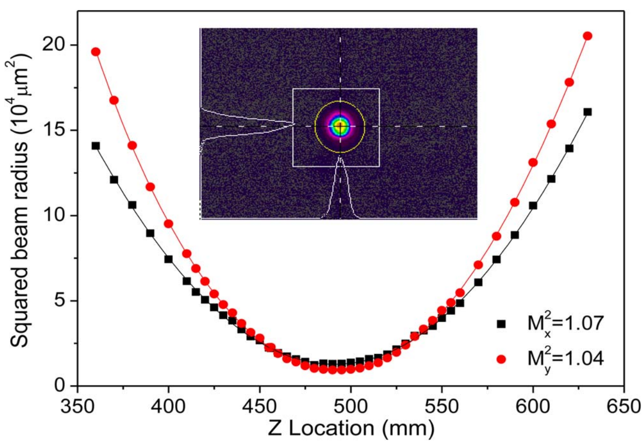


Fig. 7. Squared beam diameter of the Pr^{3+}:$LiYF_4$ laser at 915 nm along the beam propagation direction as measured in the x and y transverse directions.

Fig. 6 reports the observed spectrum between 600 and 1000 nm by using an Ocean-Optics HR4000 Optical Spectrum Analyzer (OSA) with a resolution of 0.2 nm, as the output coupler is the one of 0.8% transmission. It clearly confirms that no other emission than the 915 nm laser emission is observed. The figure also shows the detail of the laser emission spectrum at ~915 nm. The peak wavelength is exactly registered as 914.8 nm showing a line-width (FWHM) of about 1.7 nm. According to the calculation of the longitudinal mode interval, the FWHM corresponds to about 199 longitudinal modes inside the laser cavity. Such a broad laser emission, broader than that found in the visible range, is mainly due to the broad width of the 915 nm emission line, as shown in Fig. 2. This could be exploited advantageously for Q-switching or mode-locking laser operation by using an acousto-optic modulator [15] or well-known saturable absorbers such as Cr:YAG [16], SESAM [17] or some (now-popular) graphene [18], [19].

In the end, the beam quality factor M^2 was also measured by using standard laser beam diagnostic equipment Spiricon $M^2 - 200$. The results are reported in Fig. 7. The output coupler is the one of 0.8% transmission at 910 nm. The fitting to the data gives M^2 factors in the x and y dimensions of about 1.07 and 1.04, respectively. The x direction is parallel to the a-axis of the crystal, i.e., transversal direction, and y to the c-axis, i.e., longitudinal direction. The M^2 factors show the good beam quality of the 915 nm laser emission, close to the diffraction limit, namely to the TEM_{00} mode.

5. Conclusion

Room temperature continuous-wave laser emission at 915 nm of an InGaN-LD-pumped Pr^{3+}: $LiYF_4$ laser crystal was demonstrated for the first time. A simple plane-concave linear cavity was configured to achieve near infrared lasing with four differently coated output couplers. The highest output power up to 77.8 mW was obtained by using a mirror with a transmission of 0.8% with a slope efficiency of about 17.2% and an optical-optical conversion efficiency of 14.1%. The round-trip losses inside the laser cavity were estimated to be about 0.45% by using the Findlay-Clay method. The measurement of the beam propagation factor M^2 shows an excellent beam quality with M^2 values of about 1.07 and 1.04 in x and y directions, respectively.

Based on these experimental results, a power scaling of the Pr^{3+}:$LiYF_4$ laser at 915 nm can be expected by optimizing the parameters of the laser configuration and/or utilizing a more powerful pumping source, such as a 1.6 W InGaN blue LD (Nichia Corporation: NDB7875) or a 5.3 W Coherent High Power OPS laser [11]. With a promoted output power, further works should be readily carried out, such as intra- or extra-cavity second-harmonic generation by using the adequate nonlinear crystal, Q-switched or mode-locked laser operation with the aid of various saturable absorbers and acousto-optic modulators, which is now already planned in our groups.

References

[1] T. Sandrock, T. Danger, E. Heumann, G. Huber, and B. H. T. Chai, "Efficient continuous wave-laser emission of Pr^{3+}-doped fluorides at room temperature," *Appl. Phys. B*, vol. 58, no. 2, pp. 149–151, Feb. 1994.

[2] J. M. Sutherland, P. M. W. French, J. R. Taylor, and B. H. T. Chai, "Visible continuous-wave laser transitions in Pr^{3+}:YLF and femtosecond pulse generation," *Opt. Lett.*, vol. 21, no. 11, pp. 797–799, Jun. 1996

[3] A. Richter *et al.*, "Diode pumping of a continuous-wave Pr^{3+}-doped $LiYF_4$ laser," *Opt. Lett.* vol. 29, no. 22, pp. 2638–2640, Nov. 2004.

[4] K. Hashimoto and F. Kannari, "High power GaN diode-pumped continuous wave Pr^{3+}-doped $LiYF_4$ laser," *Opt. Lett.*, vol. 32, no. 17, pp. 2493–2495, Sep. 2007.

[5] T. Gün, P. Metz, and G. Huber, "Power scaling of laser diode pumped Pr^{3+}:$LiYF_4$ CW lasers: efficient laser operation at 522.6 nm, 545.9 nm, 607.2 nm, and 639.5 nm," *Opt. Lett.*, vol. 36, no. 6, pp.1002–1004, Mar. 2011.

[6] A. Richter, E. Heumann, G. Huber, V. Ostroumov, and W. Seelert, "Power scaling of semiconductor laser pumped Praseodymium-lasers," *Opt. Express*, vol. 15, no. 8, pp. 5172–5178, Apr. 2007.

[7] B. Xu *et al.*, "Highly efficient InGaN-LD-pumped bulk Pr:YLF orange laser at 607 nm," *Opt. Comm.*, vol. 305, pp. 96–99, 2013.

[8] Z. Liu *et al.*, "Diode-pumped Pr^{3+}:$LiYF_4$ continuous-wave deep red laser at 698 nm," *J. Opt. Soc. Amer. B*, vol. 30, no. 2, pp. 302–305, 2013.

[9] B. Xu, P. Camy, and J. Doualan, Z. Cai, and R. Moncorgé, "Visible laser operation of Pr^{3+}-doped fluoride crystals pumped by a 469 nm blue laser," *Opt. Exp.*, vol. 19, no. 2, pp.1191–1197, Jan. 2011.

[10] B. Xu *et al.*, "Frequency doubling and sum-frequency mixing operation at 469.2, 471, and 473 nm in Nd:YAG"*J. Opt. Soc. Amer. B*, vol. 29, no. 3, pp. 346–350, Mar. 2012.

[11] V. Ostroumov, W. Seelert, and L. Hunziker, "522/261 nm cw generation of Pr:YLF laser pumped by OPS laser," *Proc. SPIE*, vol. 6451, 2007, Art. ID. 451046.

[12] J. Zhou, Z. Liu, and F. Li, "Upconversion nanophosphors for small-animal imaging," *Chem. Soc. Rev.*, vol. 41, no. 3, pp. 1323–1349, Feb. 2012.

[13] G. G. David, "A revolution in optical manipulation," *Nature*, vol. 424, pp. 810–816, Aug. 14, 2003.

[14] J. L. Adam, W. A. Sibley, and D. R. Gabbe, "Optical absorption and emission of $LiYF_4$:Pr^{3+}," *J. Luminescence*, vol. 33, no. 4, pp. 391–407, Dec. 1985.

[15] J. Kojou, Y. Watanabe, Y. Kojima, H. Nemoto, and F. Kannari, "Intracavity second-harmonic generation at 320 nm of an actively Q-switched Pr:$LiYF_4$ laser," *Appl. Opt.*, vol. 51, no. 9, pp.1382–1386, Mar. 2012.

[16] J. Gao, R. Yan, and X. Yu, "Diode-pumped passively Q-switched 916 nm laser with a Cr4+:YAG saturable absorber," *Original Res. Article*, vol. 313, no. 15, pp. 401–405, 2014.

[17] V. G. Savitski, I. M. Ranieri, A. B. Krysa, and S. Calvez, "Passively Q-switched Pr:YLF laser," presented at the CLEO: Science and Innovations (CLEO_SI), 2011, Baltimore, MD, USA, Paper: CMB7.

[18] Z. Luo *et al.*, "Multiwavelength mode-locked erbium-doped fiber laser based on the interaction of graphene and fiber-taper evanescent field," *Laser Phys. Lett.*, vol.9, no. 3, pp. 229–233, Mar. 2012.

[19] I. H. Baek *et al.*, "Efficient mode-locking of sub-70-fs Ti:Sapphire laser by graphene saturable absorber," *Appl. Phys. Exp.*, vol. 5, no. 3, Mar. 2012, Art. ID. 032701.