Randomly polarised beam produced by magnetooptically Q-switched laser

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Diode-pumped solid-state micro lasers are compact (centimetre-scale), highly stable, and efficient. Previously, we reported Q-switched lasers incorporating rare-earth substituted iron garnet (RIG) film. Here, the first demonstration of the magnetooptical (MO) Q-switch in an Nd:YAG laser cavity is performed. We fabricate a quasi-continuous-wave (QCW) diode-pumped Nd:YAG laser cavity, which is shortened to 10 mm in length and which contains an RIG film and a pair of small coils. This cavity yields a 1,064.58-nm-wavelength pulse with 25-ns duration and 1.1-kW peak power at a 1-kHz repetition ratio. Further, the polarisation state is random, due to the isotropic crystal structure of Nd:YAG and the fact that the MO Q-switch incorporating the RIG film does not require the presence of polarisers in the cavity. This is also the first report of an MO Q-switch producing random polarisation.

Since their initial development, lasers have been implemented as irreplaceable components of various applications, e.g., mass spectrometers, laser machining devices, car ignition plugs, satellite propulsion devices, and medical equipment. In particular, the Q-switching technique allows solid-state lasers to generate a short, high-powered pulse output, which is crucial for the above applications.

Previously, we proposed a magnetooptical (MO) Q-switch composed of a ferrimagnetic rare-earth substituted iron garnet (RIG) film and small coils. Magnetic garnets are well known for their large MO effects and high transmittance in the near-infrared region. However, although RIGs have potential use in optical applications such as two-dimensional integrated arrays and storage media, there are few reports of Q-switches employing these materials. In one of our previous studies, we demonstrated the MO Q-switch in a diode-pumped Nd:GdVO₄ laser system and showed the potential of this Q-switch, for which a notably compact system size was obtained (cavity length L: 10 mm). Note that such a small L is impossible using other active Q-switches, for example, electro-optic (EO) and acousto-optic (AO) Q-switches. EO Q-switches require a cubic polariser in the cavity and a high-voltage power supply for operation, whereas the AO module in an AO Q-switch cannot be made appropriately small to yield sufficient interaction and radio-frequency (RF) power supply for operation. Therefore, it is difficult to miniaturise L or the entire laser system for these Q-switches. As higher output photon densities can be achieved for Q-switched lasers with shorter length L, diode-pumped solid-state micro lasers having L values of millimetre order are attracting interest.

Although the compactness of the MO Q-switched laser incorporating RIG film was demonstrated previously, the output peak power remained small. Therefore, in this paper, a quasi-continuous-wave (QCW) pumping technique using pulsed pumping light is employed to provide higher pump energy to the lasing material. In addition and for the first time, Nd:YAG emitting randomly polarised light is used as a laser material to demonstrate the MO Q-switch. The combination of Nd:YAG and an MO Q-switch has special meaning unlike other Q-switches because a common misunderstanding is that the Q-switching using MO materials is only based on the Faraday rotation, meaning that the input light must always be in a linearly polarised state while using the MO Q-switch. Regarding the achievement of integrated actively Q-switched micro lasers, Nd:YAG is a promising lasing material. The crystal structure of Nd:YAG is similar to RIG, and these materials have similar thermal expansion coefficients; thus, RIG film can grow on the Nd:YAG via epitaxial growth techniques or bond to...
the Nd:YAG surface as Cr^{4+}:YAG$^{32,33}$. The latter material also possesses a garnet structure and a similar thermal expansion coefficient, and has been reported as an appropriate material for a passive Q-switch with high miniaturisation$^{34,35}$. Therefore, the performance of MO Q-switching using RIG in an Nd:YAG laser is important for the implementation of actively Q-switched micro lasers. Finally, the use of a different lasing material also facilitates discussion of the polarisation state of the MO Q-switched laser. The RIG-based Q-switch does not require the presence of a polariser in the cavity; therefore, the isotropic structure of the Nd:YAG must affect the output polarisation state.

**Experimental setup**

A schematic of the prepared Q-switched laser cavity is shown in Fig. 1a, with parts of the cavity components being cut away for improved visibility. A diode at 808-nm wavelength end-pumped the 0.5 at.% Nd:YAG crystal, which was $3 \text{ mm} \times 3 \text{ mm} \times 4 \text{ mm}$ in size. The Nd:YAG crystal was wrapped in foil and fixed in the water-cooled Cu heat sink, and its temperature was stabilised at 20 °C by a proportional-integral-derivative-controlled Peltier cooler. Dielectric multilayer coating was present on the input and output surfaces of the Nd:YAG, having high reflectance (HR) of 99.8% at the 1,064-nm wavelength and high transmittance (HT) of 98% at 808-nm wavelength on the input side, and 98% HT and 99.8% HR at 1,064- and 808-nm wavelengths, respectively.

A concave mirror with 300-mm curvature radius and 90% reflectance at the 1,064-nm wavelength was placed 10-mm from the Nd:YAG input surface as an output coupler. The MO Q-switch was inserted in the cavity. The RIG used in this study was the same 190-μm-thick film employed in our previous studies$^{16,17}$, which was formed via a liquid-phase epitaxy method on a 560-μm-thick single-crystalline Gd$_3$Ga$_5$O$_{12}$ substrate. The composition of this film measured by energy-dispersive x-ray spectroscopy (JEOL, JED-2201F) was Tb$_{2.0}$Bi$_{1.0}$Fe$_{4.8}$Ga$_{0.2}$O$_{12-\xi}$, where $\xi$ indicates the number of oxygen vacancies. The optical loss characterized by a spectrophotometer (UV-3150, Shimadzu) was 108 dB/cm at the wavelength of 1,064 nm. The Faraday rotation angle at 1,064-nm wavelength measured via the rotating analyser method was $2.4 \times 10^3$ °/cm. Further, the figure of merit (FOM) defined by the Faraday rotation angle divided by the absorption was 222 °/dB. Maze-shape magnetic domains appeared in the RIG with an average width of ~50 μm. A pair of small coils with 5.3-mm diameter sandwiched the RIG and were connected to a pulse current generator, which applied a peak current of 56 A with 3-μs duration for the applied pulsed field. The generated field applied to the coil was estimated to be more than 200 Oe, which is the saturation field of the RIG film.

Figure 1b shows the beam diameter in the cavity estimated using the ABCD matrix method$^{24}$, along with the refractive indexes of the cavity components. The beam diameter in the RIG was approximately 245 μm, which is five times larger than the average widths of the magnetic domains in the RIG film. The laser output was simultaneously monitored by an energy meter (Ophir, VEGA) and an InGaAs-based fast-response optical detector (Thorlabs, DET10C/M).

**Results**

**Peak power and beam quality.** The pulse width $\tau_p$ and peak power of a Q-switch laser are proportional and inversely proportional to $L$, respectively$^{18}$. The relation between $\tau_p$ and $L$ is expressed as$^{14}$

$$\tau_p \approx \frac{r \eta (r)}{r - 1 - \ln r} \tau_c = \frac{r \eta (r)}{r - 1 - \ln r} \left( \frac{2L}{c \delta} \right)$$

where $r$ is the inversion ratio, $\eta$ is the energy extraction efficiency, $\tau_c$ is the cavity delay time, $c$ is the velocity of light, and $\delta$ is the cavity loss before Q-switching. The values of $c$, $r$, $\eta$, and $\delta$ were $3.0 \times 10^8$ m/s, 1.063, 0.908, and 0.002, respectively.

![Figure 1. Diode-pumped magnetooptical (MO) Q-switched laser. (a) Schematic of laser cavity setup. The rare-earth substituted iron garnet (RIG) film was sandwiched by a pair of coils and its magnetisation was modulated by a pulsed field. The minimum cavity length $L$ was 10 mm. (b) Beam diameter (thick orange line) estimated using ABCD matrix method and refractive indexes (thin blue line) in cavity.](https://www.nature.com/scientificreports/)
were fixed to 1 kHz and 200 cross-section of Nd:YAG (electric-pulse rise time applied to the coils was fixed to 15 μs). The duration between the pumping-pulse fall time and the pumping energy was changed by modulating the diode-output. The duration between the pumping-pulse fall time and the pumping energy became saturated for a pumping energy of more than 3.1 mJ. Such a saturation characteristic shows good agreement with previous experimental reports using passive Q-switch lasers. The output energy is constant until additional pulses are generated. Hence, a single pulse was obtained in this setup.

To determine the minimum input energy for Q-switching, the pumping energy was changed by modulating the diode-output. The duration between the pumping-pulse fall time and the electric-pulse rise time applied to the coils was fixed to 15 μs. Figure 3 shows the output energy obtained as a function of the input energy for these conditions. The threshold was 2.9 mJ and the output energy became saturated for a pumping energy of more than 3.1 mJ. Such a saturation characteristic shows good agreement with previous experimental reports using passive Q-switch lasers. The output energy is constant until additional pulses are generated. Hence, a single pulse was obtained in this setup.

**Output polarisation.** The output-pulse polarisation state was analysed using a quarter-wave (λ/4) plate and an analyser. Initially, the output power was measured with a rotating analyser, and the results indicated that the state exhibited circular or random polarisation. Then, a λ/4 plate was inserted between the output coupler and the analysers. The power change was monitored using a fast-response optical detector (Thorlabs, DET10C/M). As shown in Fig. 4, the λ/4 plate exerted no influence on the polarisation; therefore, random polarisation of the output was confirmed.
Discussion

In the polarisation state measured using the $\lambda/4$ plate shown in Fig. 4, small dent-like features are apparent. However, these features were caused by the $\lambda/4$ plate insertion and are unrelated to the output state produced by the MO Q-switch laser. Note that Nd:YAG has an isotropic crystal structure and emits unpolarised light. Further, although an MO Q-switch using an isotropic lasing material has been reported, this is the first report of a randomly polarised output for an MO Q-switch laser, because the RIG-based MO Q-switch does not contain polarisers. If one needs to control the polarisation state, changing the lasing material from an isotropic crystal to an anisotropic one would be the easiest way. For the laser cavity using Nd:GdVO$_4$, which emits linearly polarised light, a circularly polarised output was obtained. Thus, the results obtained in this study show that the MO Q-switch using RIG film can be used with various lasing materials. These results are contrary to the mechanism of an MO Q-switch explained by Faraday rotation. While we do not have a clear model explaining the entire mechanism of the MO Q-switch, these results would help.

Overall, this study demonstrates integrable MO Q-switching using RIG film in an Nd:YAG laser system for the first time. The 10-mm-long cavity produced 1.1-kW peak power and a 27-ns-long output at a centre wavelength...
of 1064.58 nm via QCW diode pumping, generating randomly polarized pulses. The repetition ratio was 1 kHz. In addition, the output polarisation state was confirmed to be random and an M² value of 3.7 was obtained. In this laser system, the Q-switch and the laser wavelengths have a similar crystal structure; therefore, the MO Q-switch and the Nd:YAG can be combined into actively Q-switched micro lasers, similar to epitaxial growth or bonding of passive Q-switches on laser materials (e.g., Cr³⁺:YAG on Nd:YAG)²⁻³. The experimental evidence provided in this study advances this research field toward the realisation of actively controllable integrated micro lasers.

References

1. Martens, J., Gazetic, J., Berden, G. & Oomens, J. Structural identification of electron transfer dissociation products in mass spectrometry using infrared ion spectroscopy. Nat. Commun. 7, 11754 (2016).
2. Li, Q., Zheng, Y., Wang, Z. & Zuo, T. A novel high-peak power double AO Q-switches pulse Nd:YAG laser for drilling. Opt. Laser Technol. 37, 357–362 (2005).
3. Taira, T. & Kobayashi, T. Q-switching and frequency doubling of solid-state lasers by a single intracavity KTP crystal. IEEE J. Quantum Electron. 30, 800–804 (1994).
4. Taira, T., Mukai, A., Nozawa, Y. & Kobayashi, T. Single-mode oscillation of laser-diode-pumped Nd:YVO₄ microchip lasers. Opt. Lett. 16, 1955 (1991).
5. Zaykowski, J. J. & Mooradian, A. Single-frequency microchip Nd lasers. Opt. Lett. 14, 24 (1989).
6. Graham-Roeve, D. & Won, R. Lasers for engine ignition. Nat. Photonics 2, 515–517 (2008).
7. Tsuchekane, M. & Komura, Y. High peak power, passively Q-switched microchip laser for ignition of engines. IEEE J. Quantum Electron. 46, 277–284 (2010).
8. Phipps, C. et al. Review: Laser-ablation propulsion. J. Propuls. Power 26, 609–637 (2010).
9. Chen, J., Qian, H., Han, B., Shen, Z. & Ni, X. Investigation of the momentum coupling coefficient for propulsion by Nd:YAG laser at 1064 nm in atmospheric and water environment. Opt. - Int. J. Light Electron Opt. 124, 1650–1655 (2013).
10. Gonzales, D. A. & Baker, R. P. Micropropulsion using a Nd:YAG microchip laser. SPIE-Int. Soc. Opt. Eng. 4760, 752–765 (2002).
11. Skorczakowski, M. et al. Mid-infrared Q-switched Er:YAG laser for medical applications. Laser Phys. Lett. 7, 498–504 (2010).
12. Mola, E. Microchip lasers and their applications in optical microsystems. Opt. Mater. 11, 289–299 (1999).
13. Maleki, A., Kavoshi Tehrani, M., Saghafifar, H. & Moghtader Dindarlu, M. H. Experimental study of electro-optical Q-switched pulsed Nd:YAG laser. Chinese Phys. B 25, 34206 (2016).
14. Koechner, W. Solid-State Laser Engineering. (Springer, New York, 2006).
15. Bhandari, R. & Taira, T. 6 MW peak power at 532 nm from passively Q-switched Nd:YAG/Cr³⁺:YAG microchip laser. Opt. Express 19, 19135 (2011).
16. Goto, T. et al. Magneto-optical Q-switching using magnetic garnet film with micromagnetic domains. Opt. Express 24, 17635 (2016).
17. Goto, T. et al. Magnetic domains driving a Q-switched laser. Sci. Rep. 6, 38679 (2016).
18. Goto, T. et al. Optical Tamm states in one-dimensional magnetophotonic structures. Phys. Rev. Lett. 101, 14–16 (2008).
19. Yoshimoto, T. et al. Magnetophotonic crystal with cerium substituted yttrium iron garnet and enhanced Faraday rotation angle. Opt. Express 28746 (2016).
20. Nakamura, K. et al. Improvement of diffraction efficiency of three-dimensional magneto-optic spatial light modulator with magnetophotonic crystal. Appl. Phys. Lett. 108, 16 (2016).
21. Isogai, R. et al. Thermomagnetic writing into magnetophotonic microcavities controlling thermal diffusion for volumetric magnetic holography. Opt. Express 24, 822 (2016).
22. Velsko, S. P., Ebbes, C. A., Comaskey, B., Albrecht, G. F. & Mitchell, S. C. 100 W average power at 0.53 μm by external frequency conversion of an electro-optically Q-switched diode-pumped power oscillator. Appl. Phys. Lett. 64, 3086 (1994).
23. Ray, A., Das, S. K., Mukhopadhyay, S. & Dutta, P. K. Acousto-optic-modulator-stabilized low-threshold mode-locked Nd:YVO₄ laser. Appl. Phys. Lett. 89, 221119 (2006).
24. Yariv, A. Quantum Electronics. (Wiley, New York, 1975).
25. Yu-Ye, W. et al. Numerical modelling of QCW-pumped passively Q-switched Nd:YAG lasers with Cr³⁺:YAG as saturable absorber. Chinese Phys. Lett. 25, 2880–2883 (2008).
26. Bhandari, R., Taira, T., Miyamoto, A., Furukawa, Y. & Tago, T. 3 MW peak power at 266 nm using Nd:YAG:Cr³⁺:YAG microchip laser and fluxless-BBO. Opt. Mater. Express 2, 907 (2012).
27. Sato, Y. & Taira, T. Highly accurate interferometric evaluation of thermal expansion and dn/dT of optical materials. Opt. Mater. Express 4, 876–888 (2014).
28. Taira, T. RE³⁺-ion-doped YAG ceramic lasers. IEEE J. Sel. Top. Quantum Electron. 13, 798–809 (2007).
29. Krennrich, D., Knappe, R., Heinrich, B., Wallenstein, R. & F.H. J. A comprehensive study of Nd:YAG, Nd:YAlO₃, Nd:YVO₄, and Nd:Yd:V₃O₅ lasers operating at wavelengths of 0.9 and 1.3 μm. Part 2: Passively mode locked-operation. Appl. B. Lasers Opt. 92, 175–183 (2008).
30. Park, M.-B. & Cho, N.-H. Structural and magnetic characteristics of yttrium iron garnet (YIG, Ce:YIG) films prepared by RF magnetron sputter techniques. J. Magn. Magn. Mater. 231, 253–264 (2001).
31. Ubuzski, S. B. et al. Growth and characterization of YAG:Cr³⁺ epitaxial films. J. Cryst. Growth 311, 353 (1999).
32. Pavel, N., Saikawa, J., Kurimura, S. & Taira, T. High average power diode end-pumped composite Nd:YAG passive Q-switched by Cr³⁺:YAG saturable absorber. Ipn. J. Appl. Phys. 40, 1253–1259 (2001).
33. Fu, S. G., Ouyang, X. Y. & Liu, X. J. Passively Q-switched Nd:YAG/Cr³⁺:YAG bonded crystal microchip laser operating at 1112 nm and its application for second-harmonic generation. Appl. Opt. 54, 8805 (2015).
34. Pavel, N., Tsunekane, M. & Taira, T. Composite, all-ceramics, high-peak power Nd:YAG/Cr³⁺:YAG monolithic micro-laser with multiple-beam output for engine ignition. Opt. Express 19, 9378–9384 (2011).
35. Izhin, I. et al. Development of monolith Nd:YAG/Cr³⁺:YAG passively Q-switched microchip laser. Proc. SPIE 5958, 595823 (2005).
36. Spühler, G. et al. Experimentally confirmed design guidelines for passively Q-switched microchip lasers using semiconductor saturable absorbers. J. Opt. Soc. Am. B 16, 376–388 (1999).
37. ISO/DIS 11146. Test methods for laser beam parameters: Beam width, divergence angle and beam propagation factor. (1995).
38. Zhou, F. Z. et al. Compact, magneto-optic Q-switched, neodymium-doped bismuth germinate crystal (Nd:BGO) laser pumped by a laser diode. Appl. Opt. 34, 2–4 (1995).

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Author Contributions
R.M. measured the optical and magnetic properties. T.G. and T.T. fabricated the laser cavity system. J.P. and M.M. designed and fabricated the pulsed magnetic field generator. Y.N., H.T., P.L. and H.U. discussed the magnetooptical Q-switching effect. T.G. and M.I. conceived the original concept of this device and organised the development of the associated system and devices.

Additional Information
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