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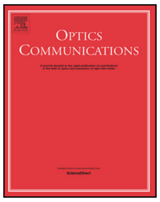

# Visible Q-switched pulse laser oscillation in Pr-doped double-clad structured waterproof fluoride glass fiber with graphene

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## ABSTRACT

We successfully generated a visible Q-switched pulse train at 636 nm in a Pr-doped double-clad structured waterproof fluoride glass fiber with graphene as a saturable absorber (SA) and calculated the slope efficiency as 22.1%. The average radio frequency and the average pulse width of all observed pulses were respectively measured as 633 kHz and 185 ns. We also discussed the required intensity to generate Q-switched operation in graphene using extrapolation and estimated the required intensity of Q-switched oscillation with graphene from kW/cm2 to MW/cm2 depending on wavelength.

## 1. Introduction

Visible lasers are widely applicable in many technologies, including medicine, laser processing, display, biology, metrology, and optical storage [1,2]. We are studying multi-wavelength laser oscillation in a Pr-doped waterproof fluoride glass fiber (Pr:WPFGF). This new optical fiber is based on AlF$_3$ system fluoride glass. Since this fiber has four different absorption peaks, red (637-nm-band), orange (605-nm-band), green (523-nm-band), and blue (482-nm-band), it is a useful device in the visible spectra range [1]. In 2016, we developed a Pr-doped double-clad structured waterproof fluoride glass fiber (Pr:DC-WPFGF) and demonstrated a laser oscillation in the fiber. This was the world's first fiber with a single mode and a double-clad structure with an AlF$_3$ system fluoride glass [3]. Our next target is creating a more powerful laser with higher intensity and pulsed operation.

Several reports of visible nanosecond pulse generation in a Pr gain medium such as Pr:YLF and Pr:ZBLAN have been published [4–10]. Cr$^{4+}$:YAG [4], topological insulators (TIs) [5], two-dimensional (2D) transition-metal dichalcogenides (TMDs, WS$_2$, and MoS$_2$) [6], Graphene-Oxide [7], Gold nanoparticles [8], Copper Nanowires [9] and black phosphorus [10] were used as a saturable absorber (SA) [4–10]. Carbon-based SAs, such as graphene, have been well studied in the infrared region [11]. We also demonstrated a Q-switched Pr:WPFGF laser at 603 nm with graphene SA [12].

In this paper, we show a Q-switched Pr:DC-WPFGF laser at 636 nm with graphene SA and discuss the required intensity of Q-switched operation in graphene.

## 2. Experimental setup of a Q-switched Pr:DC-WPFGF laser in the 637-nm-band with graphene

The experimental setup of a Q-switched Pr:DC-WPFGF laser in the 637-nm-band with graphene is shown in Fig. 1. A 10-cm-long Pr:DC-WPFGF was doped with Pr$^{3+}$ at the fiber core, the concentration is 3000 ppm. The core and inner-clad diameters are 5.2 and 14 μm, respectively, and the core NA is 0.08. Since the V-number was calculated as 2.045 at 639 nm, the fiber is in a single-mode [3]. The GaN laser diode (#NDB7875E, NICHIA Corp.) was used as a pump source emitting at 442 nm with a maximum output of 1.6 W. The oscillation wavelength of the laser diode (LD) was kept constant, the temperature was kept at 25 °C using a Peltier element and a fan. The laser cavity is composed of direct dielectric multilayer coating on the fiber end surface as an output coupler (PR = 86%@639 nm, AR@442 nm) and a graphene saturable absorber mirror (GSAM), which has a structure of that the graphene was put between the thin silica glass (surface accuracy $\lambda/10$) and the high-reflection mirror surface. The CVD graphenes on Cu foil (GRAPHENE SUPERMARKET) have 10% $\sim$ 30% bilayer islands, and graphene is grown on both sides of the copper foil. In GSAM's manufacturing

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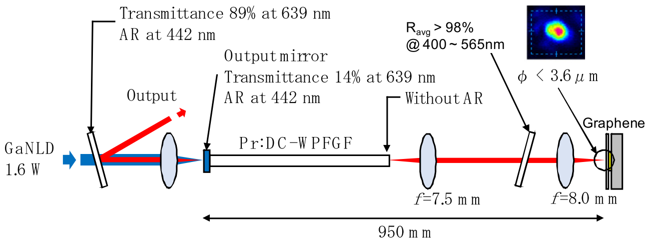

**Fig. 1.** Experimental setup of Q-switched pulse laser oscillation in Pr:DC-WPFGF.

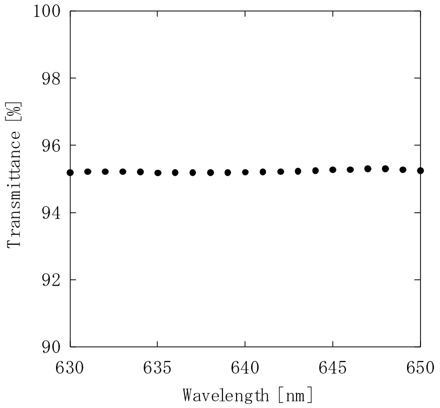

**Fig. 2.** Transmittance of graphene used in this study.

process, after etching the Cu foil, since 1 ∼ 2 layers of graphenes can be overlapped, it is assumed that the GSAM has 2 ∼ 4 layers of graphene. In few-layer graphene, 2.3% optical absorption increases linearly with the number of layers, which indicates that the number of the layer can be estimated by observing the optical contrast in the sample [11]. From the transmittance of graphene used in this study shown in Fig. 2, the graphene has a transmittance of 95.2% at 636 nm, indicating that it has two or more layers. The fiber's output beam was collimated by a collimation lens ($f$ = 7.5 mm, NA = 0.30; #A375TM-B, THORLABS) and concentrated on the GSAM by a focus lens ($f$ = 8.0 mm, NA = 0.50; #C240TME-A, THORLABS). Next the focal point beam diameter was measured by a micro-beam profiler (#MBP-100-USB, Newport), and we estimated the value of the beam diameter on the GSAM after cavity optimization. We adopted a backward excitation system. ASE noise on GSAM was removed by a filter (R = 98% @ 400∼565 nm, R < 5% @ 637 nm). Laser output was flipped by a dichroic mirror (T = 89% @ 639 nm, AR@442 nm) that was placed between the GaN-LD and the fiber.

## 3. Results

The spectrum of 637-nm-band Q-switched pulse laser oscillation is shown in Fig. 3. The laser oscillation wavelength and the FWHM of the spectrum width were 636.1 nm and 2.47 nm by an optical spectrum analyzer (#AQ6317B, ANDO, resolution: 0.01 nm), respectively. The input–output characteristics of 637-nm-band Q-switched pulse laser oscillation in Pr:DC-WPFGF are shown in Fig. 4. The leakage pump power through the fiber was 189 mW at 1156 mW of the launched pump power. Absorption in 100 mm Pr:DC-WPFGF was 83.7%. The slope efficiency and the threshold power of the laser oscillation were calculated as 325 mW and 22.1%, respectively. The maximum average output power was measured as 139 mW at 967 mW of absorbed power by a power meter (#model 3A, OPHIR). This result is about 70 times more efficient than the previously reported Q-switched Pr:WPFGF laser in the 605-nm-band with graphene SA by optimization of OC reflectance and optical system [12]. The beam diameter on the GSAM was measured as <3.6 μm by a micro-beam profiler. The maximum power density on the GSAM was estimated to be <200 MW/cm$^2$, the damage of GSAM did not observe. The pulse waveform of 637-nm-band Q-switched pulse laser oscillation at the maximum output is shown in Fig. 5. As shown the pulse was instability, the average radio frequency and the average pulse width of all observed pulses were measured as 633 kHz and 185 ns by an oscilloscope (2.5 GHz; #TDS7254b, Tektronix) with a photodiode (2 GHz; #DET025A/M, THORLABS), respectively. Thus, the average pulse peak power and the average pulse energy were calculated as 2.84 W and 0.28 μJ, respectively. The temporal stability of the Q-switched operation was very poor. Two considerations were discussed for GSAM and multi wavelength oscillations as follows. In GSAM, the effective area of the homemade GSAM was about several% due to the poor surface condition. There is a possibility that this resulted in the instability of the pulse. In multi wavelength oscillation, from the spectrum shown in Fig. 3, since this pulse laser has multiple peaks and 2.47 nm wide spectrum, it oscillates at multiple wavelengths. Since the pulse oscillations of multiple wavelengths were simultaneously generated, the pulse waveform is chaotic. If multi-wavelength oscillation can be suppressed, pulse energy can be improved.

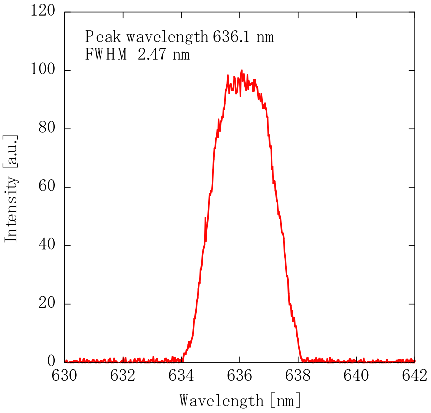

**Fig. 3.** Spectrum of 637-nm-band Q-switched pulse laser oscillation.

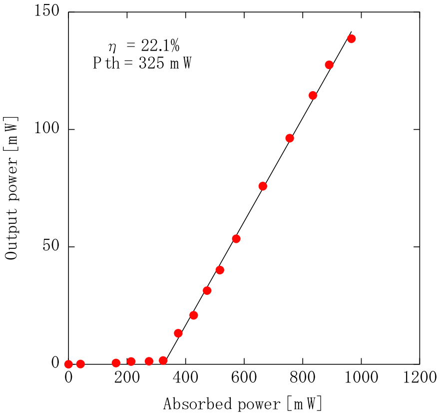

**Fig. 4.** Input–output characteristics of 637-nm-band Q-switched pulse laser oscillation.

## 4. Discussion

In this section, we discuss the required power intensity on the GSAM for generating Q-switched laser oscillation in the visible region with graphene using extrapolation. The required power intensities on the GSAM were calculated for generating both Q-switched and mode-locked

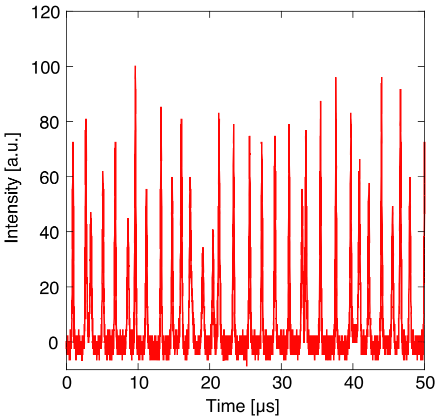

**Fig. 5.** Pulse waveform of 637-nm-band Q-switched pulse laser oscillation.

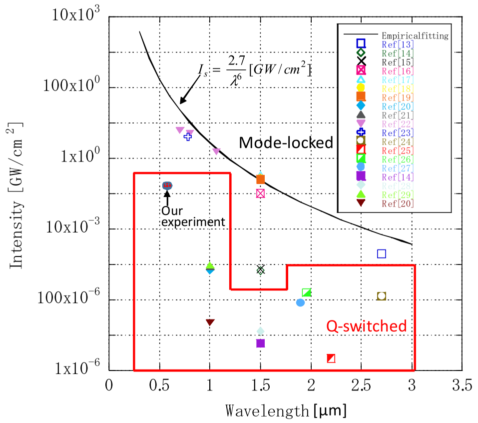

**Fig. 6.** Q-switched pulse laser and saturation intensity with graphene [13–29].

pulse lasers from previous reports, and the calculated intensities are plotted versus wavelengths in Fig. 6 [13–29]. The data points were without considering the number of graphene layers. The enclosed data points denote the saturation intensities for Q-switched pulse generation. Fig. 6 shows that the intensity of Q-switched oscillation is required from kW/cm$^2$ to MW/cm$^2$. In our experiment, the maximum power density on the GSAM was estimated to be <200 MW/cm$^2$, and therefore, adequate power density was irradiated on the GSAM for Q-switched pulse oscillation. On the other hand, to achieve mode-locked oscillation, SA must be sufficiently saturated. The saturation intensity of graphene depends on the wavelength [11,30]. An empirical fit to the experimental data of saturation intensities $I_S$ (in GW/cm$^2$) has been suggested as a function of wavelength $\lambda$ (in µm) [11,30]:

$$I_S = 2.7/\lambda^6 \text{ [GW/cm}^2\text{]} \tag{1}$$

If the saturation intensity of the graphene is required, as shown in Fig. 5, the threshold intensity of mode-locked oscillation at the visible region can exceed the GW/cm$^2$ level. In these experimental results, the required intensity on the graphene is estimated to be about 100 times larger than the intensity obtained by this experimental setup. To achieve mode-locked oscillation, higher laser intensity must be obtained in the cavity. In addition, when a phase mismatch due to material dispersion in the fiber and suppression of multi wavelength oscillations are optimized, we will be able to achieve a primary visible mode-locked fiber laser in the future.

## 5. Conclusion

We successfully generated a visible Q-switched pulse train at 636 nm in Pr:DC-WPFGF with graphene SA and demonstrated for the first time that graphene is a useful SA for Q-switched pulse oscillation in the visible range. We also discussed the required intensity of Q-switched operation in the visible region with graphene using extrapolation and estimated the required intensity of Q-switched oscillation with graphene from kW/cm$^2$ to MW/cm$^2$ depending on wavelength.

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