Angular momentum (AM) is a universal physical concept and can be carried by a rotated particle. The orbital and spin are two types of AM. Similar with rotated particles such as electrons, light can also have AM when it has a helical phase or rotated polarization direction \([1, 2]\). Both of them can transfer torque \([3, 4]\). However, the spin AM per photon has only three values \(\pm \hbar\) corresponding to the linear and circular polarization with different rotated directions, and the orbital AM per photon \(\hbar l\) is generated by the helical phase and determined by the topological charge or azimuthal mode index \(l\) \([2]\). Up to now, their generation \([4-6]\), propagation dynamics \([7, 8]\), entanglement \([9]\), interaction with matter \([10]\), etc., have been drawing much attention over the past few decades, since they belong to the wave-particle duality \([2]\) and reveal the nature of the optical angular momentum \([11]\). Laguerre-Gaussian \((\text{LG}_{p,l})\) laser modes are a type of eigen modes of the laser cavity and carry orbital angular momentum equal to \(\hbar l\) per photon. The previous investigation has identified that the astigmatism effect is essential for the generation of high-order eigen laser modes, no matter for the Hermite–Gaussian \((\text{HG}_{p,l})\) or \(\text{LG}_{p,l}\) laser modes \([12]\). However, the introduction of astigmatism effects into the laser cavity would reduce the lasing efficiency since the astigmatism would reduce the mode-matching degree between pump and oscillating beams \([13]\).

In the lasing process, the heat is unavoidable and mainly caused by the quantum defects \([14]\). The thermal effects generated are considered to be deleterious on the laser output performance, especially in the high-power lasers. Thermal induced lens is the direct result of thermal effects whose focal length is tunable by the absorbed pump power \([15]\) and change the size of oscillating modes. The size of oscillating high-order eigen modes of the laser cavity is proportional to their order and sizes of the fundamental modes determined by the laser cavity. By mode-matching between the pump and oscillating beams, the order of achieved laser modes can be driven thermally and no obvious reduction of the optical efficiency is generated. In the universal neodymium doped crystal lasers, the most serious thermal effects are generated during the lasing process at the wavelength of 1.3 \(\mu\)m, since the quantum defect are the largest. The lasers at the wavelength about 1.3 \(\mu\)m have great applications in the specific fields of medical treatment, optical fiber communication, efficient production of red radiation by frequency doubling, etc. \([16]\), aside from the absorption of some specific matter at this wavelength. In this letter, we demonstrate the thermally driven continuous-wave (cw) and pulsed \(\text{LG}_{p,l}\) laser modes at the wavelength of 1.3 \(\mu\)m with tunable topological charges. The results also identified that graphene can be used as a saturable absorber for the generation of pulsed optical vortex.

The pump source was a fiber-coupled laser diode (LD) with a central wavelength around 808 nm. The core size of the fiber was 100 \(\mu\)m, with tunable topological charges. The results also identified that graphene can be used as a saturable absorber for the generation of pulsed optical vortex.
used for the generation of cw and pulsed optical vortex was shown in Fig. 1. The gain medium was Nd doped (Lu0.5Y0.5)2SiO5 (Nd:LYSO) crystal, cut along its c axis and with a size of 3 mm×3 mm×10 mm, whose end faces were polished and uncoated. The crystal was wrapped with indium foil and mounted in a water-cooled copper block with cooling temperature of 20 °C. The emission peak with the longest wavelength was located at about 1.36 μm [17], which determined the quantum defect was 40.5% during lasing process in this wavelength band. A plane-concave resonant cavity was used to run the laser. A concave mirror (M1) with a curvature radius of 200 mm, which was high-transmission (HT) coated at 808 nm and 1.06 μm to 1.08 μm, and highly refractive at 1.3 μm to 1.4 μm, was used as the input mirror. A flat mirror (M2) was the output coupler, which was also HT coated at 1.06 μm to 1.08 μm with an optimized transmission of 5% at 1.3 μm to 1.4 μm. The oscillation at 1.06 μm to 1.08 μm in the cavity was suppressed by the HT coating at this wavelength band. The length of the cavity was about 20 mm. For the pulsed lasers, a multi-layered graphene with the initial transmission of 87% was used as the saturable absorber which was inset between the gain material and output coupler.

The output power performance was shown in Fig. 2. The threshold was measured to be 0.45 W and the maximum output power was 1.36 W under the absorbed pump power of 6.7 W with the optical conversion and slope efficiency of 20.3% and 21.8%, respectively. The achieved typical transverse patterns were also shown in this figure, corresponding to the output power and absorbed pump power. From this figure, it could be found that the output transverse modes belong to LGp,l with the topological charge of ℓβ. Based on the ABCD matrix, the oscillating modes was infinite if there was no thermal lens generated in the crystal, since the cavity used was a concave-plano one. The LGp,l mode size could be approximately shown as ω0(l+1)1/2 [18, 19], where ω0 was the fundamental mode size which can be calculated by the ABCD matrix. With the method presented by Song et. al [20], the thermal focal length could be measured with this cavity. Based on the calculation and measurement of the thermal focal length, it could be found that, in the used laser cavity, the LGp,l mode size was reduced as the decrease of the thermal induced focal length if the focal length is larger than about 3 mm. The modes with ℓ=1 well matched with the pump beam in the pump range from 2.86 to 4.99 W, however, the modes with ℓ=2 was well matched from 4.99 to 5.7 W. Increase the pump power over than 5.7 W, the p=1 mode appeared which was shown in the inset of Fig. 5. Considering the large quantum defects (40.5%), relatively poor thermal properties of the used crystal [21] and its low absorption efficiency (30.8%) at the pump beam, we did not increase the pump power further, so as to avoid the cracking. Therefore, it could be concluded that the generated optical vortex was thermally driven and the mode-matching was the selection rule for the order and topological charge of LGp,l modes. To identifying the LGp,l modes driven thermally, the cooling temperature was promoted to 25 °C which generated the higher LG0,1 mode threshold (over than 3 W), since the thermal focal length is determined by the difference in temperature between the cooling sides on and the pump core in the crystal [15].

To confirm the topological charge of achieved LG0,1 modes, a mode converter made up of two identical cylindrical lenses was used to transform the LG0,1 to
HG0,0 modes, which could introduce a \( \mathbb{F} \) to the decomposition of LG0,l [2]. The plain surfaces of the two lenses were set to be paralelled to each other with the axis of the cylinder pointing vertically. In the experiment, we prepared the distance between the two cylindrical lenses to be precisely \( 2f \), where \( f \) was the focal length of the two lenses. Figure 4 showed the transverse patterns of the LG0,l modes and converted HG0,l modes. From this figure, we could identify the achieved LG0,l modes possessing the topological charges of \( l=1 \) and \( 2 \). In all the lasing process, there was no astigmatism effect in the lasing cavity and the slope efficiency of 21.8% was normal for the quantum defects of 40.5%. We believed that the efficiency could be improved if the laser crystal was suitable coated at the lasing wavelength.

Fig. 4. The transverse pattern of the laser beam. Upper line: the achieved LG0,l modes. Down line: the converted HG0,l modes corresponding the LG0,l modes.

Graphene has been investigated as a universal saturable absorber for the generation of pulsed lasers. By inserting the graphene into the cavity, the optical pulses were generated. The passively Q-switched laser performance was also presented in Fig. 2. The threshold was 0.47 W, a bit larger than the cw one. The highest output power was 0.53 W under the absorbed pump power of 6.7 W, with the slope efficiency of 8.5%. The repetition rate and pulse width were recorded with a DPO7104 digital oscilloscope (1 GHz bandwidth and 10 Gs/s sampling rate, Tektronix Inc.). As showed in Fig. 3, the repetition rate increased from 8.4 kHz to 79 kHz and the pulse energy increased from 5.69 \( \mu \)J to 6.71 \( \mu \)J in all pump power range. The shortest pulse was 102 ns under the pump power of 6.7 W. The pulse profile with the width of 102 ns and typical repetition rate of 79 kHz were also presented in the inset of Fig. 3. It should be noted that the thresholds of LG0,1, LG0,2 and LG1,0 modes were respective 2.46 W, 4.5 W and 5.3 W, obviously smaller than the corresponding cw thresholds. The observed LG0,1, LG0,2 and LG1,0 modes are almost similar with those shown in 4. Considering the peak power of the output pulses, the intracavity peak intensity of the pulsed lasers was about 48 times larger than the cw one, which indicated that the nonlinear refractive index effects in the pulsed regime should be responsible for the lower threshold of high-order modes. From the pulsed results, no topological charge was found to be lost, which identified that there was no angular momentum transfer between the graphene and vortex pulses and the graphene could be used as a saturable absorber for the vortex pulses. Using an optical spectrum analyzer, the laser spectrum was measured to be located at about 1.36 \( \mu \)m, which is shown in Fig. 5.

In conclusion, thermally driven cw and pulsed optical vortex are directly generated by mode-matching selection. Considering the large quantum defects and specific application, the optical vortex at the wavelength of 1.36 \( \mu \)m are demonstrated. The results also identified that graphene can be used as a pulse modulator. We believe that the generated cw and pulsed optical vortex should find some promising applications in quantum optics, investigation of the interaction of orbital angular momentum of photons and matter, nonlinear optics, optical communications, etc.

This work is supported by the National Natural Science Foundation of China (Nos. 51025210, 51102156 and 51272131), and Shandong Province Young and Middle-Aged Scientists Research Awards Fund (BS2011CL024).

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