1. Introduction

In dual-wavelength spectroscopic technology, dual-wavelength lasers with frequencies at two peaks separated by a few terahertz (THz) are widely used in various applications such as THz imaging and spectroscopy [1, 2], high-resolution interferometry [3], optical and sensing technology [4, 5], etc.

Recently, optical vortex beams carrying orbital angular momentum (OAM) have attracted intensive research interest for their broad applications in optical tweezers [6], optical communications [7–9], and quantum entanglement [10, 11] by utilizing the unique properties of the helical phase. Furthermore, dual-wavelength OAM beams are beneficial for advanced applications due to their combinative characteristics of both a helical phase and dual-wavelength spectrum. A dual-wavelength OAM beam based on a Nd:Lu2O3 laser was previously reported [12], but the two spectral peaks are unbalanced and unadjustable. Hence, optimization of the spectral profile and improvements in the tunability to match modern spectroscopy applications are still required. As a new crystal with an ultra-broad emission band, Yb:CaGdAlO4 (CALGO) demonstrates an outstanding performance to satisfy these requirements [13–17]. Our group has recently demonstrated a wavelength-tunable vortex beam with the highest order of 15ℏ OAM [18]; however, the conditions for high-stability dual-wavelength emission have never been investigated.

In this work, we demonstrate a dual-wavelength OAM beam with two stable spectral peaks separated by a few THz. By combining the feature of a broad emission band of Yb:CALGO and a special coating of cavity mirrors, dual-wavelength generation in a diode-pumped solid-state laser (DPSSL) can be effectively obtained. Using a π/2 convertor [19], a vortex beam is converted from the Hermite–Gaussian (HG) mode produced by off-axis pumping. Under certain pump powers and off-axis displacements, stable OAM beams with a dual-wavelength spectrum can be generated. The
spectral stability was experimentally verified due to the fact that the $l\hbar$ OAM beam with two spectral peaks of 1046.1 nm and 1057.2 nm (separated by 3.01 THz) could operate for more than 3 h.

2. Experimental design

The experimental setup, as depicted in figure 1, includes two main parts: the off-axis-pumped DPSSL for generating a high-order HG mode and a Mach-Zehnder interferometer for generating and measuring the OAM.

For the DPSSL, a $2 \times 2 \times 4$ mm$^3$ (4 mm along the laser direction) a-cut 5 at.%-doped Yb:CALGO with two end surfaces antireflective- (AR) coated for laser and pump light was used as a gain medium, which was wrapped with indium foil and conductively water cooled at a temperature of 18 °C. The laser was generated by a linear plano-concave resonator with a concave output coupling mirror (OC, a radius of curvature of 300 mm) and a flat dichroic mirror (DM 1, with a high-reflection- (HR) coated laser and an AR-coated pump light). Based on the polarization-dependent emission spectra (figure 2: the $\sigma$-polarization is superior at 1000–1080 nm), the laser was $\sigma$-polarized due to the gain competition. The crystal was pumped by a 976 nm fiber-coupled laser diode (Han’s TCS, core: 105 $\mu$m, NA: 0.22, highest power: 110 W) with a pump waist radius of 200 $\mu$m through a coupler including two identical AR-coated convex lenses ($F_1 = F_2 = 60$ mm) and DM$_1$. The DM$_2$ (an AR-coated laser and a HR-coated pump light) was used to filter the residual pump light.

For the interferometer, the two arms were formed by two beam splitters (BS$_1$ and BS$_2$, 45° incidence, T:R = 1:9) and two 45° HR mirrors (HR$_1$ and HR$_2$). For the first arm, the laser was incident into the $\pi/2$ convertor after being focused by a convex lens ($F_1 = 180$ mm) and converted into Laguerre–Gaussian (LG) mode:

\[
LG_{p,l}(r, \phi, z) = \sqrt{\frac{2p!}{\pi (p+|l|)!}} \frac{1}{w(z)} \left( \frac{\sqrt{2}}{w^2(z)} \right)^{|l|} \exp \left[ -\frac{r^2}{w^2(z)} \right] \exp \left[ -i (2p + |l| + 1) \tan^{-1} \left( \frac{z}{z_R} \right) \right],
\]

where $r = \sqrt{x^2 + y^2}$, $\phi = \tan^{-1}(y/x)$, the 1/e radius of the Gaussian term is given by $w(z) = w(0) \sqrt{(z^2 + z_R^4)/z_R^2}$ with $w(0)$ being the beam waist, $z_R$ is the Rayleigh range, and $L_p^{|l|} (\cdot)$ is an associated Laguerre polynomial; the produced LG$_{0,l}$ beam with an OAM of $l\hbar$ passed through an attenuator and a convex lens ($F_3 = 150$ mm) and was captured by a CCD camera (Spiricon, M2-200s) after being focused by a convex lens ($F_4 = 150$ mm); the $\pi/2$ convertor included two
identical convex-plane cylindrical lenses ($f = f_1 = f_2 = 25$ mm) with a separation of 35.4 mm ($\sqrt{2} f$); the transmittance of the attenuator could be adjusted by changing the filters. For the second arm, a confocal telescope including two convex lenses ($F_5 = 60$ mm, $F_6 = 300$ mm) with an aperture was used to convert the laser into a near plane wave, which was captured by the CCD and formed the interference pattern:

$$I = \left| LG_0, l(r, \phi, z) + \eta LG_0,0(r, \phi, \infty) \exp \left[ \frac{i \theta_x x + \theta_y y}{\lambda} \right] \right|^2,$$

where $\eta$ is the intensity ratio of the two beams and $\theta_x$ ($\theta_y$) represents the inclined angle in a horizontal (vertical) direction.

The laser spectrum was measured by an optical spectrum analyzer (Agilent, 86140B). The laser power was measured by a thermopile power-meter (Ophir, FL250A-LP1-DIF).

Thanks to the broad and flat emission band (approximately 80 nm) of Yb:CALGO [14, 15], it is possible to directly generate broad-band wavelength-tunable and dual-wavelength lasers in oscillators [16, 17]. A broad-band coating on cavity mirrors is elaborately designed to provide enough longitudinal mode-gain competition for realizing the wavelength-tunable property. As the HR mirror of the laser resonator, DM1 was AR-coated at 976 nm and HR-coated at 1040–1080 nm. The output transmittance of the OC was about 2% at 1030–1080 nm, among which a slight rise existed as the wavelength increased. The absorption and emission cross sections of Yb:CALGO and the transmittance curves of DM1, DM2, and the OC mirrors are shown in figure 2.

3. Results and discussion

3.1. Dual-wavelength emission property of Yb:CALGO

Considering the broad emission spectrum with a plateau profile of Yb:CALGO and the broadband coating design used in our experiment, the strong gain competition makes it possible for two superior longitudinal modes to form a dual-wavelength spectrum. As expected, we successfully observed dual-wavelength emission under some pump powers. Figure 3 depicts the power and spectral evolution when the cavity and pump light were strictly coaxial. The pump threshold of the laser oscillator was around 8.3 W. The output spectrum maintained a single-peak profile until the pump power increased to 32.1 W, at which a dual-wavelength was observed. Afterwards, we continuously increased the pump power from 32.1 W–46.8 W, and the dual-wavelength oscillation was maintained while the spectral intensity of the two peaks varied versus the pump power.

3.2. Generation of dual-wavelength vortex beam

In our experiment, the vertical and horizontal off-axis distance of OC, $\Delta x$ and $\Delta y$, can be precisely adjusted to generate a high-order HG mode along an inclined direction. A HG$_{0,l}$ mode placed along the 45$^\circ$ diagonal direction can be directly converted into $lh$-OAM beam (LG$_{0,l}$ mode) via a pair of cylindrical lenses [19]. The output mode of the DPSSL is mainly dependent on the pump power ($P_p$) and off-axis distance $\Delta r = \sqrt{\Delta x^2 + \Delta y^2}$. According to our experimental results, we depicted the $P_p$–$\Delta r$-mode map to reveal the principle of mode evolution shown in figure 4(a). The pump threshold is 8.3 W with a TEM$_{00}$ output when the cavity is strictly coaxial. If we increase the pump power to 14.5 W and adjust the OC with the off-axis distance about 250 $\mu$m, a $1h$-OAM beam can be generated. Similarly, continuously increasing the pump power and off-axis distance to (18.9 W, 320 $\mu$m), (21.6 W, 350 $\mu$m), and (24.1 W, 380 $\mu$m) can lead to the generation of $2h$, $3h$, and $4h$ OAMs respectively. The interference patterns to verify the vortex beam with various OAMs are theoretically and experimentally demonstrated in figure 4(a). The vortex patterns are obtained

Figure 3. The laser power and spectrum evolution versus the pump power when the cavity and pump light were strictly coaxial ($\Delta r = 0$). Inserts: corresponding measured spectrum profiles in the evolution.
when the two interference beams are coaxial, i.e. $\theta_x = \theta_y = 0$ in equation (2). When we fixed the pump power at 21.6 W and continuously increased the off-axis distance until the nonlasering state, the dual-wavelength spectrum could be obtained accordingly with the generation of OAM, as shown in record I in figure 4(a). We noted that the $1\hbar$- and $2\hbar$-OAM beams in this process can overlap with the dual-wavelength region. When we fixed the pump power at 32.1 W, a similar evolution could also be observed—the spectrum first changed from a single-peak shape to a dual-wavelength shape and then could return to a single-peak but with a different center wavelength, as shown in record II in figure 4(a). After recording the spectral evolutions versus the off-axis distance many times at different pump powers, we obtained an overlapping region between the OAM beam states and dual-wavelength spectrum states, as shown in figure 4(b), which reveals that a corresponding dual-wavelength OAM beam can be produced. As can be seen, there is a dual-wavelength region that

Figure 4. $P_p-\Delta r$-mode map: (a) the principle of mode evolution with pump power and off-axis distance. Insets (upper): the theoretical and experimental interference patterns to verify the vortex beam with various OAMs. Insets (right): the spectrum evolution with off-axis distance increasing under fixed pump powers at 32.1 W and 21.6 W, noted as record I and record II; (b) the single-wavelength and dual-wavelength regions; the thick dash line marks the track where the OAM can be tuned maintaining the dual-wavelength spectrum; at the dot positions, the OAM can be tuned to the adjacent value by adjusting the pump power.

Figure 5. A comparison of single- and dual-wavelength regions in a $P_p-\Delta r$-mode map using crystals of different sizes: (a) $2 \times 2 \times 4 \text{ mm}^3$ (4 mm along the laser direction) and (b) $4 \times 4 \times 2 \text{ mm}^3$ (2 mm along the laser direction).
The gain length is too short to provide strong gain competition. However, the flat sheet-shaped crystal is a drawback in our previous work [18], we use a 4×4×2 mm² beam emission, which is related to the laser gain and aperture is an important parameter to influence dual-wavelength vortex duality rather than a 2×2×4 mm² crystal (thin-rod shape). However, the flat sheet-shaped crystal is a drawback of stable dual-wavelength vortex beam emission because the gain length is too short to provide strong gain competition. Figure 5(a) and (b) show the results of single- and dual-wavelength regions in $P_p\Delta r$-mode maps when using 2×2×4 mm² and 4×4×2 mm² crystals respectively. Through the comparative results, the dual-wavelength region when using a 4×4×2 mm² crystal is much smaller than that of the 2×2×4 mm² case. We only observed a limited region that can overlap the dual-wavelength state and OAM state. Therefore, the condition for generating a stable dual-wavelength emission is different to the condition for generating stable high-order modes. Using a flat sheet-shaped crystal can effectively enlarge the OAM-tunable region, while using a thin rod-shaped crystal can be beneficial to obtain a stable dual-wavelength vortex beam.

3.3. Stability of a dual-wavelength vortex beam

To test the stability of the dual-wavelength vortex beams, the spectrum of the 1h-OAM vortex beam ($P_p \approx 35.0$ W, $\Delta r \approx 300$ m) was recorded for more than 3h, as shown in figure 6. The dual-wavelength spectrum is well maintained with one peak at 1057.2 nm and the other one at 1046.1 nm and the intensities of the two peaks were approximately equal. The standard deviations of the two center wavelengths were 0.881 nm and 0.754 nm respectively. The profile of the two spectral peaks was very balanced and the two center wavelengths were separated by 11.1 nm (corresponding to 3.01 THz), which is satisfactory for applications of dual-wavelength spectroscopic techniques.

4. Conclusion

In conclusion, we demonstrate a stable dual-wavelength vortex beam generated from a Yb:CALGO DPSSL with a $\pi/2$ convertor. The dual-wavelength spectrum and OAM can be flexibly controlled by the off-axis distance and pump power due to the broad-emitting-band property of Yb:CALGO and the coating design. We depicted the $P_p\Delta r$ map where the overlapping region between the dual-wavelength spectrum and OAM beams reveals the generation of corresponding dual-wavelength OAM beams. We experimentally tested the stability of the dual-wavelength vortex beam using a 1h-OAM beam with two spectral peaks at 1046.1 nm and 1057.2 nm (separated by 3.01 THz) which is capable of steadily operating for more than 3 h. The dual-wavelength OAM beam separated by a few THz possesses great potential for scaling the applications of OAM beams such as THz spectroscopy and high-resolution interferometry.

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Figure 6. The stability verification: the dual-wavelength spectrum evolution of the 1h-OAM beam recorded for 3h under a pump power of 21.6 W and an off-axis distance of about 300 μm.
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