中国光学（中英文）
Chinese Optics
Ei 核心期刊

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引用本文:
靳昊澍, 刘辉, 许思源, 陆宝乐, 白晋涛. 基于Yb:CALGO晶体激光器的偏振复用[J]. 中国光学, 2023, 16(6): 1475–1481. doi: 10.37188/CO.EN–2023–0005
JIN Hao-shu, LIU Hui, XU Si-yuan, LU Bao-le, BAI Jin-tao. Polarization-multiplexing of a laser based on a bulk Yb:CALGO crystal[J]. *Chinese Optics*, 2023, 16(6): 1475-1481. doi: 10.37188/CO.EN-2023-0005

在线阅读 View online: https://doi.org/10.37188/CO.EN–2023–0005

第 16 卷　第 6 期
2023 年 11 月

中国光学（中英文）
Chinese Optics

Vol. 16　No. 6
Nov. 2023

文章编号　2097-1842(2023)06-1475-07

Polarization-multiplexing of a laser based on a bulk Yb:CALGO crystal

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Abstract: The polarization-multiplexing of a laser based on a medium with a large gain bandwidth and a high thermal conductivity can benefit dual-frequency and dual-comb lasers' spectral bandwidth and power. This paper presents a demonstration of the polarization-multiplexing of a laser based on a bulk Yb:CALGO crystal. The polarization multiplexing is realized by sandwiching the gain crystal with two birefringent crystals which are cut at 45° to their optical axis. This sandwich-configuration creates inside the cavity two orthogonally polarized beams which are spatially separated only in the sandwich-configuration part but collinear in other part. Meanwhile, a single pump beam is also split into two beams automatically, matching the two cavity modes. This configuration also allows the gain crystal to be located in at the waist of cavity modes, which benefits the pumping efficiency. The laser outputs watt-level power with a slope efficiency exceeding 30%. A dual-frequency operation with terahertz frequency separation is realized by inserting an etalon into the cavity.

Key words: polarization-multiplexing; Yb:CALGO crystal; dual-frequency lasers; dual-wavelength lasers; dual-comb lasers

基于 Yb:CALGO 晶体激光器的偏振复用

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摘要: 基于大增益带宽和高热导率晶体的偏振复用激光技术可以提高双频激光器和双光梳激光器在输出光谱范围和功率方面的性能。本文提出一种基于 Yb:CALGO 晶体的偏振复用激光器。将两片与光轴成 45°角切割的双折射晶体放置在增益晶体的前后两侧形成三明治结构, 利用双折射晶体的偏振特性使腔内激光形成只在三明治结构部分具备空间分离其余部分共线的偏振方向互相垂直的两种模式。同时, 这种三明治结构既能使单束泵浦光能够自动分离为两束空间分离匹配的泵浦光, 也可以使腔内增益晶体放置在腔内模式腰斑位置处, 与泵浦光达到更好的模式匹配, 提高光泵浦效率。最终测得的激光输出功率达到瓦量级并且斜率效率超过 30%。在腔内加入标准具后, 实现了频差为太赫兹量级的稳定双频激光运转。

收稿日期: 2023-02-13; **修订日期:** 2023-02-27

基金项目: 国家自然科学基金(No. 62005215); 陕西省自然科学基础研究计划(No. 2019JCW-03); 西安市科技计划(No. 202005YK01)

Supported by National Natural Science Foundation of China (No. 62005215); Natural Science Basic Research Program of Shaanxi Province (No. 2019JCW-03); Science and Technology Program of Xi'an (No. 202005YK01)

关　键　词: 偏振复用；Yb:CALGO 晶体；双频激光器；双波长激光器；双梳激光器

中图分类号: O432.1+2　　　**文献标志码:** A　　　**doi:** 10.37188/CO.EN-2023-0005

1 Introduction

Multiplexing a laser in a single cavity is the foundation of dual-frequency lasers (DFLs)[1-3] and dual-comb lasers (DCLs)[4-6]. DFLs have been broadly applied in fields such as high spectral purity microwave signal generation and distribution[2], atomic clocks[7] and terahertz generation[8]. DCLs are attractive for dual-comb spectroscopy[9] and dual-comb-based ranging[10].

Various strategies have been exploited to multiplex a laser in a single cavity. DFLs have been used for this purpose by utilizing polarization anisotropy[2], spatially dependent losses[3, 11], intracavity spectral filters[12], and spatial hole burning effects[13]. Particularly, by adjusting the intracavity birefringence, the DFLs created by polarization-multiplexing possess broadband tunability and the capability of realizing fast active phase stabilization with electro-optical crystals[1, 14]. These properties are also interesting for DCLs in examples such as those based on a mode-locked integrated surface-emitting laser MIXSEL[15] and a solid-state gain medium[5] with polarization-multiplexing. In this kind of polarization-multiplexed laser, the coupling between the two lasers is usually detrimental to their mutual coherence. Introducing a spatial separation in the gain medium can effectively reduce the coupling. The spatial separation can be subtly created by inserting a 45°-cut birefringent crystal (BC) when light is reflected by a plane mirror at one end of the laser cavity[1], or by using spatial multiplexing[4]. However, that spatial separation also decreases the optical pumping efficiency due to the mode mismatching between single-beam pumping and dual-beam lasing. Dual-beam pumping can avoid mode mismatching, but it complicates the pumping system. Additionally, this way of introducing spatial separation also constrains the gain medium such that it must be located between the plane's end mirror and the BC. However, some laser designs need the gain medium to be placed at the waist of cavity mode[16].

Another important aspect of the DFLs and DCLs is the bandwidth of their gain medium, which affects the beat-frequency tunability of DFLs or the spectral bandwidth of DCLs. During the past decade, the diode-pumped passive mode-locked lasers based on the Yb:CALGO gain crystal has been demonstrated to be able to generate watt-level sub-100 fs short pulses[17-19].

This high-performance laser benefits from the broad and smooth gain profile, and the high thermal conductivity of the gain crystal. The gain bandwidth of Yb:CALGO is evaluated to be about 80 nm, contrasting to that of a Yb:YAG crystal being 9 nm. The thermal conductivity of 2 at.% Yb:CALGO (6.3 and 6.9 $W\cdot m^{-1}\cdot K^{-1}$ along the *c*-axis and *a*-axis, respectively) is higher than that of 5 at.% Yb:YAG crystals (5.7 $W\cdot m^{-1}\cdot K^{-1}$)[20]. The high thermal conductivity supports multi-watt average output power in mode-locked lasers and allows them to reach tens of watts under continuous wave operation[21]. These advantages in spectrum and thermal conduction are attractive for the DFLs and DCLs.

In this paper, we demonstrate a high-power polarization-multiplexed laser with a bulk Yb:CALGO crystal as the gain medium. The bulk Yb:CALGO crystal is sandwiched by two intracavity BCs which are cut at 45° to its optical axis. The pump and intracavity lasers are divided into two beams with simultaneously crossed polarization. With this laser multiplexing configuration, a spatial separation is created and only happens at the sandwiched section, allowing the gain medium to be located at the waist of the cavity mode to achieve an effective mode matching. The properties of the polarization isotropy in the lasing, the output power, and the spectra are investigated in detail. By inserting an etalon into the cavity, stable dual-wavelength operation is achieved.

2 Experiment

The laser cavity is a *Z* shape as shown in Fig. 1. The gain medium is a bulk (3 mm×3 mm×3 mm) c-cut Yb:CALGO crystal (Castech) with a 3 at.% doping level. A multimode fiber-coupled semiconductor laser with a central wavelength of 976 nm is used for pumping and the maximum available pump power is 50 W. The diameter of the fiber core is 105 μm and the value of the numerical aperture is 0.22. All the crystals are coated with an anti-reflection (AR) coating at 980–1 100 nm to reduce the intracavity losses. The Yb:CALGO crystal is wrapped in a layer of indium foil and held by a copper holder to efficiently remove the heat in a water cooling system. During the experiment, the water temperature was stabilized at 15 °C. Under a non-lasing condition, the absorption rate of a single pass-through is about 34%. This absorption rate can be improved by using a gain medium with a longer absorption length, or by using pump lasers with a central wavelength closer to the absorption peak, namely 979.5 nm.

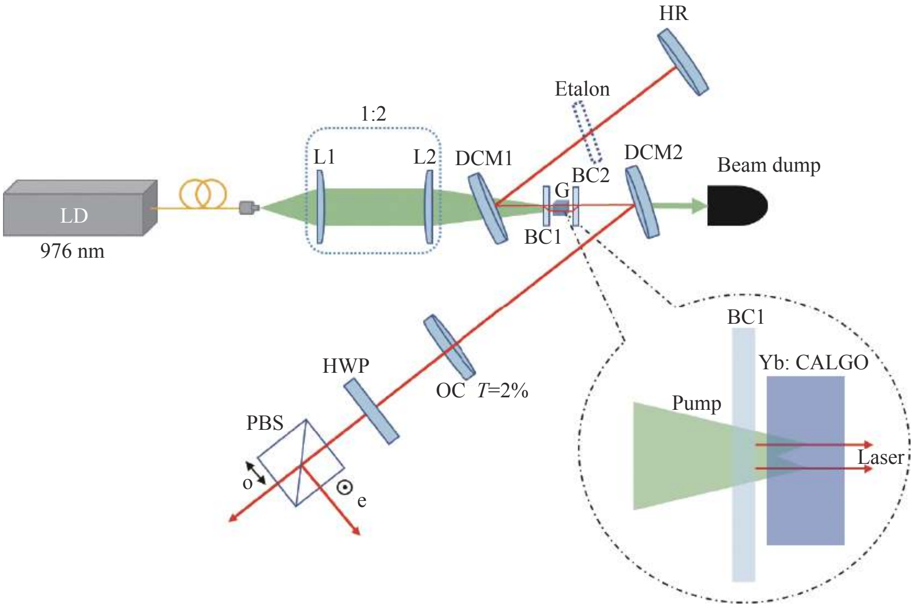


Fig. 1 Schematic of the laser polarization-multiplexed by sandwiching a Yb:CALGO crystal with two birefringent crystals. LD: fiber-coupled laser diode; DCM1, DCM2: dichroic mirrors; G: Yb:CALGO cryatal; BC1, BC2: birefringent crystals made of YVO_4; HR: high reflection concave mirror with a curvature radius of 150 mm; OC: output coupler with a curvature radius of 150 mm; L1, L2: lenses; HWP: half-wave plate; PBS: polarization beam splitter

The pump light is focused into the gain crystal through a pair of lenses with focal lengths of 50 mm and 100 mm, respectively, and the resulting pumping spot diameter is about 210 μm. The DCM1 and DCM2 are dichroic mirrors coated with AR of 900−980 nm on the back side and 1 030−1 050 nm on the front side to achieve higher reflection. The DCM2 is used to allow the pump light to emit from the cavity, thereby preventing the returning light from damaging the pump light source. HR refers to a concave mirror with a curvature radius of 150 mm and a highly reflective coating of 1 000– 1 100 nm (R>99.9%). The curvature radius of the OC is 150 mm, and the transmittance is 2%.

3 Results and discussion

Before performing the polarization-multiplexing operation, it is necessary to examine the polarization isotropy of the gain crystal. To this end, we put only one BC into the cavity, allowing only the ordinary light (o-light) to lase. Extraordinary light (e-light) was non-lasing due to the large losses caused by the beam's walk-off being transverse. The polarization of the o-light is linear, and its direction can be continuously adjusted in the transverse plane by rotating the BC. Figure 2(a) shows the output power when the light polarization was rotated. This measurement suggests that the gain medium is approximately isotropic to light polarization. This polarization isotropy results from the symmetry of the c-cut Yb:CALGO crystal. We then removed the BC and measured the output power against the absorbed pump power, showing a slope efficiency of 59% as shown in Fig. 2(b).

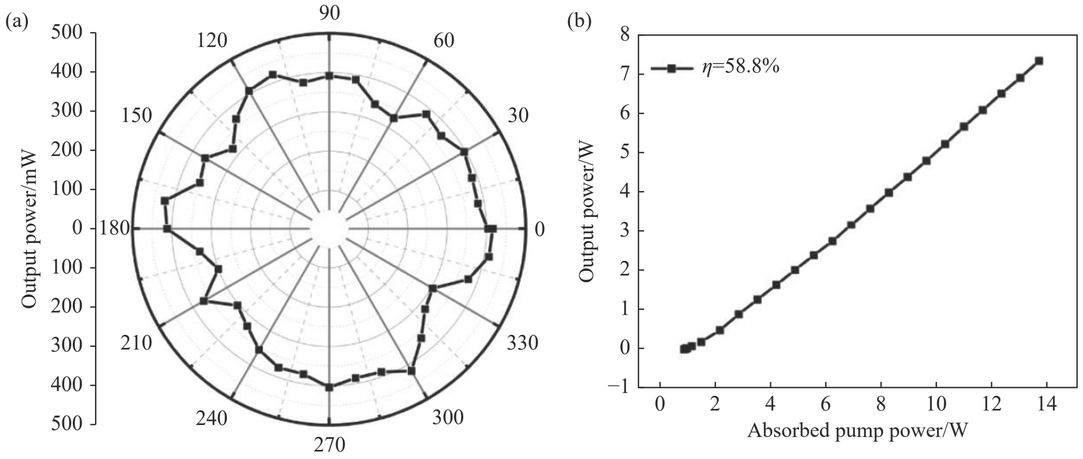


Fig. 2 Measurement results of the output power when the laser was operated in single mode. (a) Output power versus the direction of linearized laser polarization. (b) Output power versus absorbed pump power

To multiplex the laser cavity, two BCs made of YVO_4 were inserted into it with an arrangement where the gain crystal is sandwiched by the two BCs. The BCs were cut at 45° to their optical axis. The thicknesses of the BCs was 0.5 mm. Thanks to the BCs, the laser is multiplexed into two cross-polarized states. The cross-polarized beams are colinear in the cavity except in the part containing the BCs and the gain crystal. The spatial separation in the gain medium can reduce the unwanted coupling between the two laser states. Meanwhile, the single pump beam outside the cavity is also divided into two cross-polarized beams in the cavity, forming two pump spots and automatically matching the spatial separation of the laser mode in the gain medium, as shown in the zoomed-in part of Fig.1. This design makes the pumping as simple as that of single mode lasers and allows the bulk gain medium to be located at the laser mode waist to achieve mode matching for the pumping.

We measured the separation between the two pump spots by observing the maximum power passing through a pinhole held by a three-axis translation stage. As the thickness of BC was 0.5 mm, the distance between the spots of e-light and o-light was measured to be about 50 μm. According to this measurement, we can also know the direction of the transverse walk-off.

The two BCs were inserted into the cavity with identical orientation, and the transverse-walk of the e-light was chosen to be vertical. By slightly moving the position of the pump light vertically, we also found the light emitted from the two output facets of the PBS. Only one polarization state was observed when we moved the pump light further down or up so that only one polarization state was pumped. These operations confirm the coexistence of the two polarization states of the laser in the cavity. Note that to balance the pump power for each polarization, the weight for o-light and e-light was measured by using a PBS in which the direction was well aligned with the birefringent crystal. The weight was controlled by rotating the fiber used for delivering the pump 's power. Since the pump power is evenly weighted for the o-light and e-light, we use half of the total absorbed pump power to calibrate the abscissa axis for the following measurements of output power versus pump power. The output power of the coexisting polarization states was measured as shown in Fig. 3(a). It shows that the slope efficiency of each polarization state was about 30.7% and 38.5%, respectively. However, when only one polarization state was pumped, the slope efficiency was somehow close to or even higher than that when no BC was added. This can be the cause of the two pump spots partially overlapping because the diameter of each pump spot was about 210 μm while the distance to their centers was only about 50 μm.

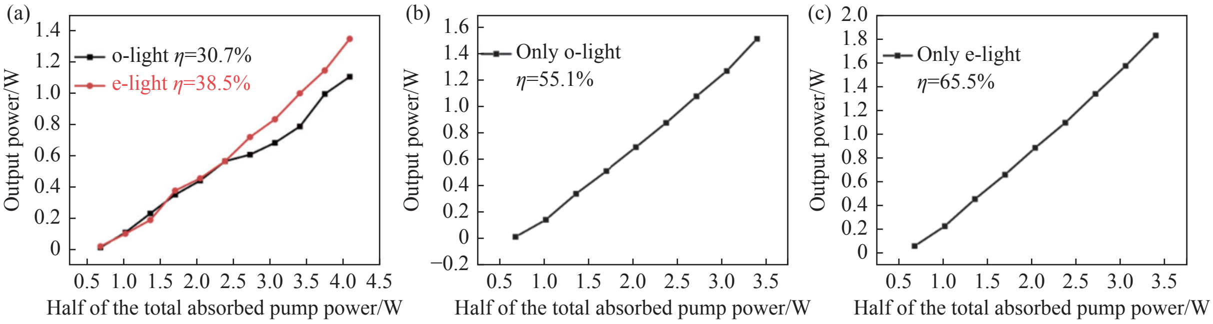
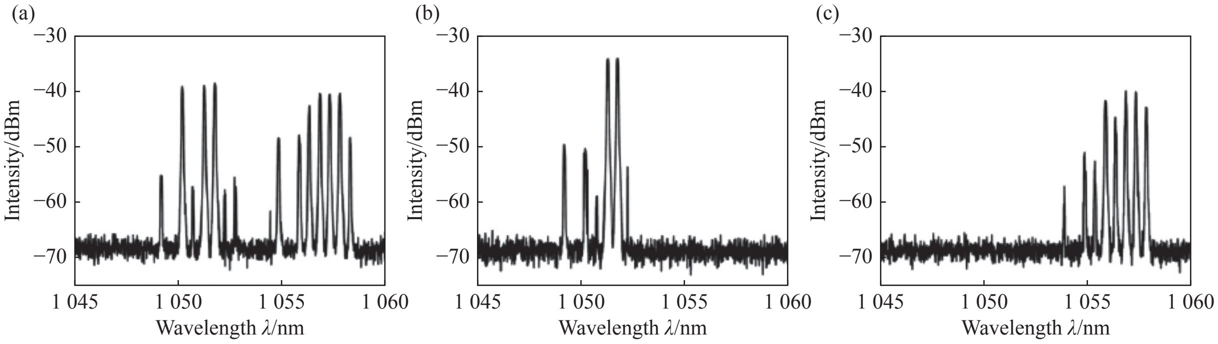


Fig. 3　Output power of the laser when the birefringent crystals were inserted into the cavity. (a) Two polarization states exist at the same time; (b) only the ordinary light is pumped; (c) only the extraordinary light is pumped

Figure 4 shows the spectra when the laser was operating in different states. When the o-light and e-light coexisted, there were two groups of peaks displayed in the spectrum as shown in Fig. 4(a). Those peaks result from the weak etalon effect of the intracavity BCs. When only one polarization state was pumped, there was only one group of peaks displayed as shown in Fig. 4(b) and Fig. 4 (c). Note that these spectra were recorded by using the maximum holding function. This phenomenon proves again that there are two polarized beams in the cavity at the same time. When an etalon was inserted into the cavity, stable dual-wavelength operation was achieved, as shown in Fig. 4(d) –(f). Due to mode selection being from the etalon, the lasing at two polarizations were at different wavelengths but they were not at similar wavelength ranges without the etalon. The etalon was made of YAG with a thickness of 250 μm, giving transmission peaks at around 1 044.6 nm and 1 050.5 nm. Fig. 4(d) shows the spectrum when the two polarized states were pumped simultaneously. By slightly moving the pump light vertically, the o-light and e-light oscillated with equal intensity. When only one polarization state was pumped, only one peak was observed as shown in Fig. 4(e) and Fig. 4(f). The wavelength separation in this dual-wavelength operation was about 6 nm, corresponding to a beat-note frequency of about 1.6 THz.



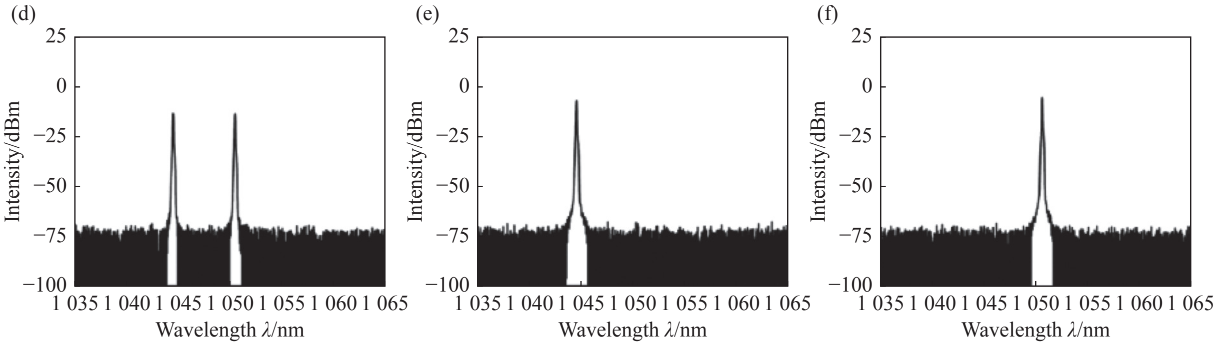


Fig. 4 Spectra in different conditions. (a)−(c) show the spectra when no etalon was used, and (d)−(f) show the spectra when an etalon was used; (a) and (d) show the spectra when the o- and e-light coexisted, while (b), (c), (e), (f) show the spectra when only one polarization state was excited

4 Conclusion

In this work, we have demonstrated a single-cavity polarization-multiplexed laser based on the Yb:CALGO gain crystal. The bulk gain medium is sandwiched by two identical intracavity BCs which are cut at 45° to their optical axis. The o-light and e-light beams are spatially separated in the BCs and gain medium, but they propagate collinearly in the rest of the cavity. The polarizations of the two laser beams are orthogonal to each other. With this design, the sandwiched gain medium can be located at the mode waist, which is conducive for highly mode-matched pumping. Meanwhile, the pumping scheme is simple, as the pump laser is divided into two polarized beams with the same spatial separation as the lasing beams in the gain medium. Since the Yb:CALGO crystal is c-cut, the gain shows isotropy for the laser polarization. The slope efficiency of the output power exceeds 30% when the laser is polarization-multiplexed. Stable dual-frequency operation with THz separation is realized when an etalon is inserted into the cavity. This work has referencial value for high-power and broadband spectra dual-comb mode-locked lasers.

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