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Polarized operation of Yb:$YAl_3(BO_3)_4$ CW and mode-locked lasers

Yanrong Song,
School of Applied Physics, Beijing University of Technology, Beijing, P.R.China, 100022;
Bronwen Taylor, Peter Dekker, Judith Dawes, James Piper,
Centre for Lasers and Applications, ICS, Macquarie University, NSW, 2109, Australia

ABSTRACT

We present a diode-pumped Yb^{3+}: $YAl_3(BO_3)_3$ (Yb:YAB) laser system and measured the polarized outputs of the CW and femtosecond mode-locked lasers with semiconductor saturable-absorber mirrors (SESAM) at the fundamental wavelength. For the CW output, polarization ratios were 88.1% and 87.2% . For the mode-locked system, polarization ratio reached 38.5%.

Keywords: Yb^{3+}: $YAl_3(BO_3)_3$, polarization, SESAM, mode-locked laser

1. INTRODUCTION

Solid-state-lasers pumped by diode lasers have become popular recently because of their compactness, robustness and convenience. The absorption bands of Ytterbium (Yb^{3+})-doped crystals at around 0.94 μm are well-suited to pumping by efficient InGaAs diode lasers that have been developed over the past decade. The small quantum defect for Yb results in highly efficient laser operation, which is not degraded by concentration quenching or excited-state absorption. High doping concentrations enable shorter crystal lengths to be employed, leading to compact diode-pumped systems. Compared with Nd^{3+}-doped materials, Yb^{3+}-doped crystals exhibit very broadband fluorescence, which allows tunability and/or ultra-short pulse generation, and the low material dispersion allows a narrower pulse width under mode-locked operation. Several Yb^{3+}-doped femtosecond mode-locked lasers have been demonstrated in recent years by the use of semiconductor saturable-absorber mirrors (SESAM) or Kerr lens mode-locking mechanisms[1-3]. Table 1 lists the parameters of selected Yb^{3+}doped crystals and the corresponding laser specifications[4-7].

Table 1: Parameters of Yb^{3+}doped crystals and corresponding laser specifications.

Parameters/ crystals	YAG	YCOB	KYW	KGW	YAB	GdCOB	BOYS
Emission bandwidth (nm)	10	44	24	25	20	44	60
Emission cross section ($10^{-20}cm^2$)	2.2	0.33	3	2.8	0.8	0.35	0.2
Absorption bandwidth (nm)	18/3	3	3.5	3.5	22	3	6
Pump wavelength (nm)	941/970	976	981	981	976	976	975
Lifetime (ms)	0.95	2.28	0.7	0.75	0.68	2.6	1.1
Thermal conductivity (W/m/K)	11	2.1	3.3	3.3	3	2.1	1.8
Pulse width - theoretical (fs)	118	—	50	47	—	27	19
Pulse width - experimental (fs)	340	210	71	100	198	90	69

Interestingly, some of these crystals have high nonlinear coefficients that give them the potential for self-frequency-doubling (SFD) properties. One advantage of SFD is that both the fundamental and the self-doubled output are emitted simultaneously (and possibly collinearly). The disadvantage is that the output is often made unstable due to the doubling, since both mode-locking and self-frequency-doubling effects depend on the intracavity power intensity.

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When they exist simultaneously, they will affect each other and introduce instability. We chose to investigate the operation of Yb^{3+}:$YAl_3(BO_3)_4$ (Yb:YAB) a highly efficient self-frequency-doubling crystal[8], with wide wavelength tenability[9]. This laser has been mode-locked with some success[4] to give pulses as short as 200 fs, but exhibited instability due to the coupling of the mode-locking and self-frequency-doubling pulse-shaping mechanisms. To achieve stable laser operation, we investigated the polarization characteristics of the crystal to first obtain stable polarized fundamental laser operation. In this paper, we describe diode-pumped, cw and mode-locked, polarized Yb:YAB laser systems, using the crystal's spectral and birefringence characteristics without employing any extra elements in the laser system.

2. EXPERIMENT

Yb:YAB is a negative uniaxial crystal. When a beam of monochromatic light enters the crystal, it separates into two waves: the ordinary wave (o-ray) and the extraordinary wave (e-ray). Normally, the spectra of the o-ray and the e-ray are termed σ-polarized and π-polarized spectra respectively. For the phase-matching condition, the polarization of the o-ray is perpendicular to the c optical axis and the polarization of the e-ray is within the plane determined by the propagation of the light and the c-axis. Our crystals were cut for Type 1 phase-matched frequency doubling at 1064 nm. This requires operation of the fundamental as the o-ray, with the frequency-doubled output as the e-ray. Figures 1 and 2 show the polarized absorption spectra and emission spectra, respectively, for Yb:YAB (The Yb dopant concentration was approximately 5 atomic %.). From these figures we can see that the absorption and emission spectra show similar polarization characteristics. For the case of the absorption spectra, the σ-polarized absorption is much stronger than the π-polarized absorption. The strongest absorption peak is at 975 nm where the absorption coefficient is 9.0 cm^{-1} while the same parameter for the π-polarized absorption is 1.1 cm^{-1} at 983 nm. In all the experiments described, the pump diode laser (from Unique-mode, Germany) was fibre-coupled with a slight residual polarization (typically 10:1). We adjusted the fiber to match the crystal polarization for maximum pumping efficiency.

The polarized emission spectra have similar properties as above. For σ-polarization, there are two main broad emission bands in the ranges 965-1002 nm and 1024-1045 nm respectively. Although the band at 965-1002 nm is much stronger than that at 1024-1045 nm, there is significant absorption in this area. The same condition occurs for the π-polarized spectra. The amplitude difference between the σ-polarization and the π-polarization emission at long wavelengths is relatively small. Thus we selected an operating wavelength of 1038nm for σ-polarization or 1030nm for π-polarization operation. In order to obtain stable fundamental polarized laser output, we needed to suppress self-frequency doubling. Because the SFD effect for π-polarization is weaker than that for σ-polarization, we used the π-polarization as the output polarization. This is described in more detail below.

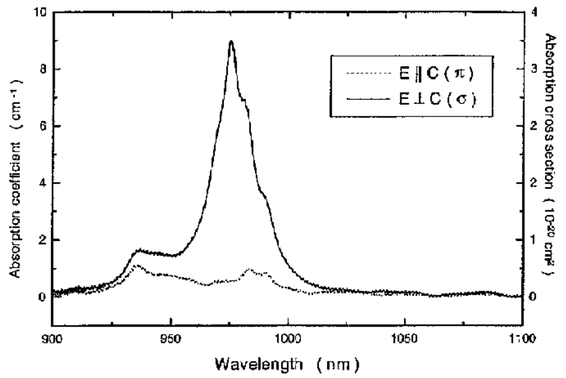

Fig. 1. Absorption spectrum. The solid line is the absorption spectrum for σ-polarization and the dashed line is for π-polarization.

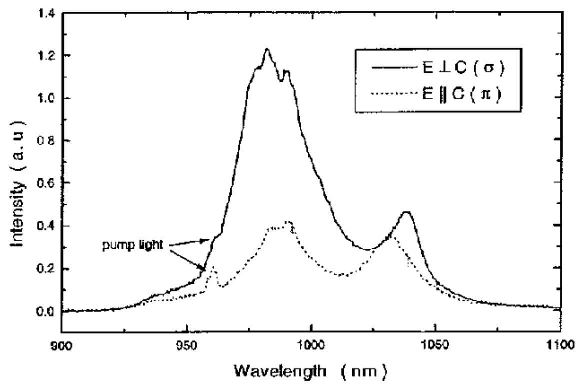

Fig. 2. Fluorescence spectrum. The solid line is the emission spectrum for σ-polarization and the dashed line is for π-polarization.

Normally a laser crystal is cut at Brewster's angle to produce a polarized laser. However, for diode-end-pumped lasers, it is necessary to use short-focal-length lenses to focus the pump light into the crystal, thus requiring that the distance between the input mirror and crystal be short (~1mm). If the crystal is put at Brewster's angle, it is difficult to locate all the elements in the cavity. Thus to control the output polarization, we selected π-polarization as the output polarization using the ray walk-off caused by the crystal birefringence.

To set up the laser, we first identified the crystal's ordinary and extraordinary light directions. The set up is shown in Figure 3. A He-Ne laser was employed as a source. The Yb:YAB crystal was placed between the two lenses. Two spots were observed (P_1, P_2) on the screen. The crystal was rotated perpendicular to the He-Ne beam, and the unmoved spot corresponded to the o-ray, while the other spot circling around this spot was the e-ray. The crystal was aligned in the mount so that the line between the two spots was parallel to the optical table, and the two polarization directions were mutually orthogonal. One polarization was parallel to the table (e-ray) and the other polarization was perpendicular to the table (o-ray). Because of the walk-off effect of the ordinary and extraordinary light, we selected the output polarization by twisting the cavity's end mirror.

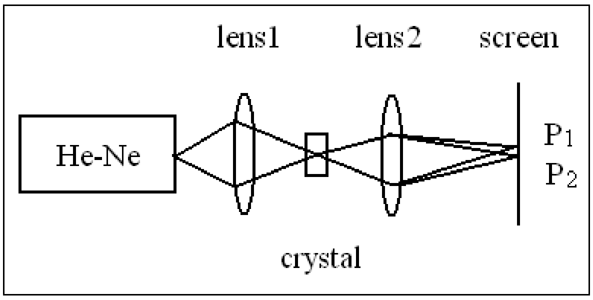

Fig. 3 Crystal polarization testing system

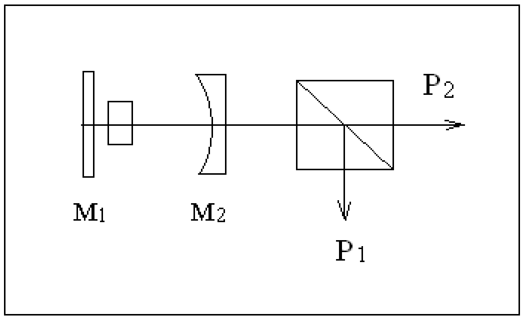

Fig. 4 Short cavity cw laser set up

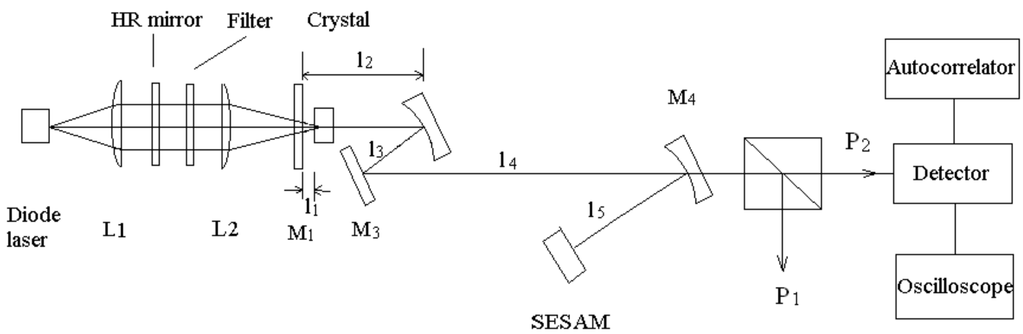

Fig. 5 System scheme of the mode locked laser

Fig. 4 shows a short plane-concave cavity that was set up to obtain CW polarized output. The maximum output power from the 975 nm fibre-coupled pump laser was 2.8 W. The pump light was aligned and focused by two lenses onto the crystal. The dimensions of the Yb:YAB crystal were 3 mm x 3 mm x 3 mm, and it was anti-reflection coated for the fundamental. The input mirror was coated for high transmission at 976nm and high reflection at 1020-1060 nm. The radius of curvature for the output mirror was 25mm, and it was ~99 % reflectivity at the laser fundamental. The polarized output was tested with a Glan prism polarizer. When we adjusted the angle of the end mirror to get the e-ray laser, the light polarized parallel to the table (P_2) was 126mW, while the output polarization (P_1) in the orthogonal direction (o-ray) was 8 mW. On the other hand, when we tried to make the o-ray polarization output larger, P_1 was 132 mW, while the e-ray polarization P_2 was 9 mW. We define polarization ratios is $\frac{|P_2 - P_1|}{|P_2 + P_1|}$. These data give polarization ratios of 88.1% and 87.2% respectively.

The same pumping and polarization measurement approach was used to investigate the SESAM mode-locked laser system. Because the doubling coefficient for the parallel polarization direction is higher than that of the perpendicularly polarized direction, we designed a parallel-polarized laser. Figure 5 shows a schematic of the whole system. We employed the SESAM (schematic of the SESAM structure shown in Figure 7) as the end mirror and saturable absorber to get mode-locked operation. The fibre-coupled pump diode laser was aligned and coupled into the laser crystal as above. The input mirror M_1 was coated for high transmission at 976nm and high reflection at 1020-1060 nm. The radius of curvature of mirrors M_2 and M_3 were 25 mm and 50 mm respectively. There were two beam waists in the cavity, one at the input mirror M_1 so that the cavity mode spot size at the crystal matched the pump beam. Another was at the SESAM so as to increase the laser intensity to reach saturation of the SESAM. The cavity length was about 80 cm. We obtained CW mode-locked laser operation with the SESAM, at a pulse repetition frequency of 133 MHz. The centre wavelength was 1030 nm. Because a concave folding mirror (M_4) was used for the output mirror, two output beams were obtained, but only one was measured, with an output power of 14 mW. In order to test the polarization degree with this situation, we employed a Glan prism as same with the short cavity.

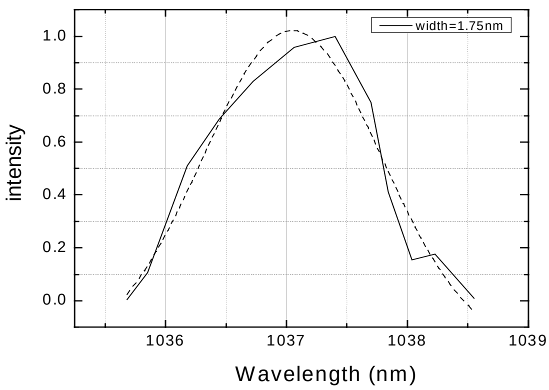

Fig. 6 The spectrum of the CW SESAM mode locked laser

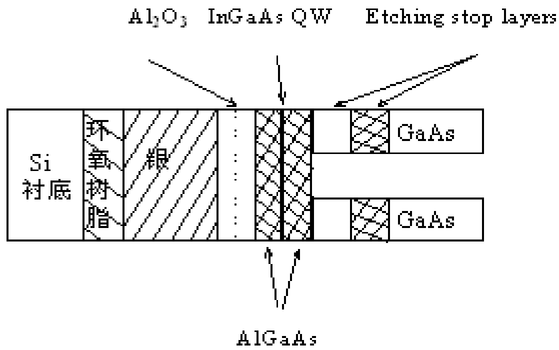

Fig. 7 Structure of SESAM

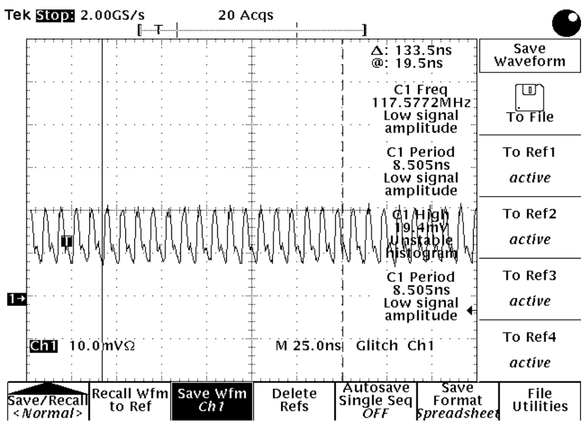

Fig. 8 The output pulse train of the SESAM mode locked laser with polarization

When the maximum output power at orthogonal direction (P_1) from the Glan prism was 4 mW, the parallel direction output power(P_2) was 9mW. If we still use the definition of the polarization ratio as above($|P_2 - P_1|/|P_2 + P_1|$), the polarization ratio reached 38.5%. Compared to the shorter CW laser, the mode-locked laser output power was much smaller. This was because we employed a high reflecting concave mirror as the output mirror, but used a 99 % transmission mirror as the output mirror in the CW set up. We would expect higher output power from the mode-locked laser with a higher transmission output coupler. The polarization ratio in the mode-locked laser was not as high as for the CW laser. The main reason was that the intracavity intensity was higher when mode locking was operating, and the orthogonally-polarized laser mode could reach threshold. Another contributing factor may be that the polarizer was not put in at the best angle. Figure 6 shows the spectrum of the pulsed laser (solid line) with a Gaussian fitting curve (dashed line). The spectrum is a near-perfect Gaussian and the pulse width is estimated from this as 640 fs. We did not compensate for the intracavity dispersion. After dispersion compensation, the pulse width would be expected to be shorter. Figure 8 shows the stability of the CW mode-locked pulse train.

3. CONCLUSIONS

In the paper, we have described two diode-pumped Yb^{3+}: $Yal_3(BO_3)_3$ (Yb:YAB) laser systems. Using the birefringence of the crystal, we controlled the polarization of the CW and SESAM mode-locked lasers without any extra elements. The approach was simple to implement, and gave a high output polarization ratio for CW operation. Further work on the mode-locked laser involves optimising the SESAM mode-locking system and the introduction of the dispersion compensation elements, to allow the production of shorter pulsewidth with a higher polarization ratio.

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