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Wavelength-stable, narrow-spectral-width oscillation of an AlGaInP diode laser coupled to a $BaTiO_3$:Co stimulated photorefractive backscattering phase conjugator

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Abstract. We have demonstrated the operation of a 639-nm cw index-guided AlGaInP diode laser coupled to a barium titanate ($BaTiO_3$) stimulated photorefractive backscattering (SPBS) phase conjugator. The SPBS process was successfully achieved by the combination of the short-wavelength diode laser and the highly doped photorefractive $BaTiO_3$:Co crystal. The spectral width of the diode laser is reduced to 7.2 pm because of the narrow spectral bandwidth of the gratings [with wave number of $K = 2k(2k$ gratings)] formed in the SPBS phase conjugator, compared with the transmission grating formed in the conventional cat conjugator, which was used previously. The SPBS phase conjugator was successfully used to suppress self-frequency scanning, and wavelength-stable oscillation of the SPBS phase-conjugator-coupled diode laser was achieved.

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External cavity operation is one means of improving spectral performance characteristics of continuous wave (cw) diode lasers, promoting single-longitudinal mode, narrow-linewidth oscillation [1, 2] as well as frequency stabilization and wavelength tunability [3]. However, a drawback of this method is the precise alignment of the external cavity required by the extremely small active region of the diode laser, which often results in excessive sensitivity of the laser system to the surrounding environment due to mechanical vibration, temperature, and so on. An attractive prospect for developing a stable external-cavity diode-laser system would use a phase conjugator as the external reflector; such a system has been referred to as a phase-conjugate cavity [4]. This type of laser cavity never requires alignment of the external phase conjugator, because the reflected phase-conjugate wave traces exactly back to the active region of the diode laser, which leads to a mechanically stable laser system.

Of the many materials which can generate phase-conjugate waves, a photorefractive ferroelectric crystal is most suitable for cw diode lasers because it does not require the high peak powers demanded by $\chi^{(3)}$ materials, stimulated Brilloum scattering materials, and so on. Specifically, a barium titanate self-pumped passive phase conjugator [5, 6] has been extensively used in versatile experiments because of the advantage that it requires only one incident beam for the self-induced four-wave mixing (FWM) process. Several demonstrations have been reported of the operation of diode lasers coupled to a phase conjugator [7–13], where two types of self-pumped phase conjugators were utilized: a “cat” conjugator [5] and a “ring” conjugator [14]. Vahala et al. [8] achieved a single-longitudinal, narrow-linewidth (< 100 kHz) oscillation of a GaAlAs diode laser with the ring conjugator which showed the good potential of phase-conjugate cavity operation. However, the linewidth of less than 100 kHz is not explainable by the spectral bandwidth of either a transmission or reflection grating self-formed in the ring conjugator, and no experimental or theoretical explanation has been reported so far. In general, the narrowed spectral width is determined by the spectral bandwidth of the photo-induced refractive grating in the phase conjugator. In the cat conjugator coupled diode laser, the total emission spectral width was determined by the spectral bandwidth of the transmission grating (approximately 1 nm) which is usually self-induced in the cat conjugator [9, 10].

In order to obtain a spectral bandwidth narrower than the 1-nm wavelength tolerance in the cat conjugator, interference between two counterpropagating beams is required, which induces gratings with wave number of $K = 2k$ ($2k$ gratings), which have the smallest possible grating spacing. Theoretical analysis [15] and experimental demonstration confirm [16] that the light diffracted from $2k$ gratings can be the phase-conjugate of the incident beam: this is commonly referred to as a stimulated photorefractive backscattering (SPBS) process. In this respect, it is anticipated that use of the SPBS conjugator would lead to much narrower spectral-linewidth operation of a phase-conjugator coupled diode laser than the previously used cat conjugator.

The other spectral feature in the phase-conjugator coupled diode laser is self-frequency scanning, in which the laser frequency automatically scans toward the blue or red [11]. The same phenomenon was also observed in the dye laser coupled to the cat conjugator [17, 18]. Although there has been some debate about the cause of self-frequency scanning [11, 17, 18], it is worth noting that this automatically induced phenomenon results in frequency-unstable oscillation and is a serious issue for versatile practical applications.

Recently, we have demonstrated wavelength-stable oscillation of an AlGaInP diode laser coupled to a $BaTiO_3$:Co phase conjugator in the geometry where the incident laser beam is perpendicular to the crystal *a* face [19]. Although we have concluded that this wavelength-stable operation is due to the SPBS process, the geometry did not evidently show that the mechanism is SPBS. In this paper, we will demonstrate the operation of a cw visible diode laser coupled to a $BaTiO_3$ phase conjugator in the geometry which significantly shows the SPBS process. We will also describe two advantages of the SPBS conjugator over a cat conjugator used in previous work. One is the improvement of spectral-linewidth narrowing of the diode laser due to the much narrower spectral bandwidth of the $2k$ gratings compared with that of the cat conjugator, and the other is suppression of self-frequency scanning, which results in wavelength-stable operation of the phase-conjugator coupled diode laser.

1 Experiment

Figure 1 shows the experimental setup. Two key factors must be taken into account for SPBS phase conjugation in the photorefractive $BaTiO_3$ crystal: laser wavelength and the dopant concentration in the crystal [20–22]. It is well known that the backscattering gain, which is necessary for the SPBS process, decreases as laser wavelength increases [21]. This means that for longer wavelengths phase conjugation is not attributed to the SPBS process, but to the FWM process (cat conjugation). Thus a short wavelength laser is required, and we chose a cw index-guided AlGaInP diode laser oscillating at the wavelength of 638.8 nm at 20 °C, which is the shortest wavelength reported so far in phase-conjugator coupled diode laser studies [8–13].

Dopant concentration also affects the mechanism of phase conjugation: backscattering gain increases approximately in proportion with increasing dopant concentration [22]. Thus, highly doped $BaTiO_3$ crystal is necessary for this experiment. The $BaTiO_3$ crystal used here ($4.2 \times 4.4 \times 5.1\,\mathrm{mm}^3$; the *c*-axis is along the 5.1-mm-long edge) is doped with cobalt (100 ppm in melt), which induces a high linear absorption coefficient at the laser wavelength. In the preliminary experiment with this crystal and an He−Ne laser (632.8 nm; almost the same wavelength as that of the diode laser), we confirmed that SPBS phase conjugation occurred with the phase-conjugate reflectivity of 80% (without Fresnel correction) in the conventional geometry where the laser beam enters the crystal by an *a* face [5]

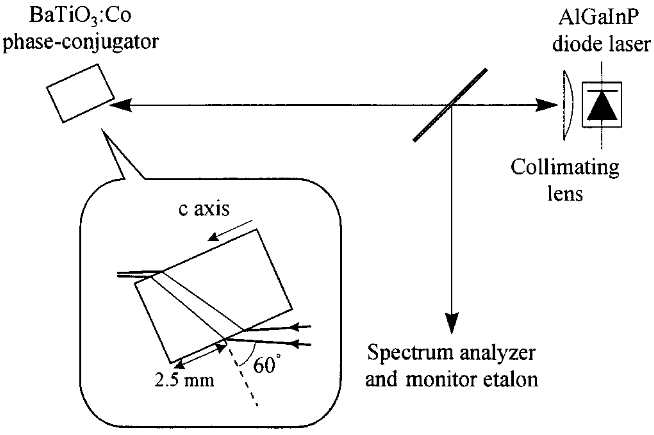

Fig. 1. Experimental setup of the index-guided AlGaInP diode laser coupled to the $BaTiO_3$:Co phase conjugator. The inset shows the precise geometry between the crystal and the incident laser beam

The AlGaInP diode laser has a cavity length of 720 μm, and the reflectivities of the front and rear facets are approximately 2 and 30%, respectively. The external cavity consists of the rear reflector of the diode laser and the $BaTiO_3$ crystal, separated by a distance of 50 cm. The diode laser without the external phase conjugator oscillates on multilongitudinal mode, and the total emission spectral width is approximately 0.36 nm (full width at half maximum) at an injection current of 80 mA (oscillation threshold current $I_{\mathrm{th}} = 63\,\mathrm{mA}$). Figure 2a shows the Fabry–Pérot pattern of the diode laser without the phase conjugator. The output power is 10 mW at this injection current. The inset of Fig. 1 shows the precise geometry of the crystal and laser beam, where the incident angle and position is 60° and 2.5 mm from the crystal $+c$ face, respectively. The polarization of the laser beam is extraordinary to the crystal. The laser beam is coupled out with a beam splitter as shown in Fig. 1, and spectral properties are ob-

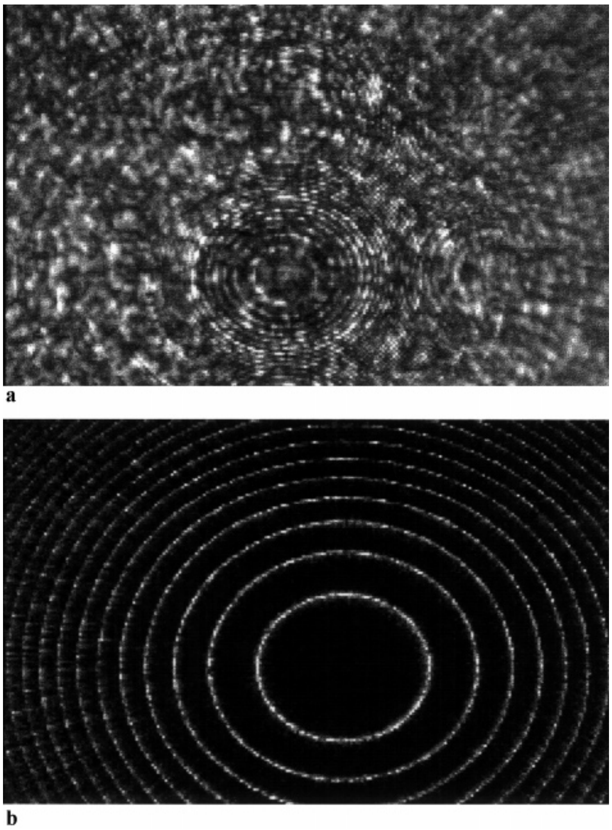

Fig. 2a,b. The Fabry–Pérot pattern of the AlGaInP diode laser: **a** without and **b** with the external phase conjugator. The total emission bandwidth of the diode laser without the phase conjugator is not resolved, because it is broader than the free spectral range of the used etalon (∼ 100 GHz) served by means of an optical spectrum analyzer (Advantest Q8381A) and a monitor etalon (FSR=100 GHz).

2 Experimental results

Figure 3a shows the temporal evolution of the wavelength and the spectral width of the phase-conjugator coupled AlGaInP diode laser with photographs of the optical paths in the crystal. At $t = 0$, the laser beam is incident on the crystal. In region (A), both the wavelength and the spectral width are the same as those of the diode laser without the external phase conjugator, which means no phase-conjugate wave is generated. A few tens of seconds from the incidence of the laser beam, the spectral width was reduced to ~ 0.12 nm [region(B)], which shows generation of the phase-conjugate wave, and it affects the spectral properties of the diode laser. From photograph (2), the mechanism of the phase conjugation seems to be the FWM process (cat conjugation); however, the phase-conjugate reflectivity is quite low (less than 1%), and the laser output power was not increased compared with the diode laser without the external phase conjugator. A small frequency hopping was observed between regions (A) and (B), and this would be due to mode hopping between the longitudinal modes in the diode laser. The discrepancy between observed frequency hopping of approximately 0.05 nm and longitudinal mode separation in the diode laser of 0.08 nm at 639 nm is due to resolution of the optical spectrum analyzer (0.1 nm). In region (C), the oscillation dynamics changed dramatically. The phase-conjugate reflectivity increased unexpectedly, and simultaneously the optical path shrank as shown in photograph (3), from which we can identify the mechanism of the phase conjugation changes into the SPBS process [23]. However, the SPBS process lasted only for a few moments; the optical path changed into that shown in photograph (2) again, and phase-conjugate reflectivity quickly decreased. The repetition between increase and decrease of phase-conjugate reflectivity was observed repeatedly, as shown in Fig. 3b. This periodic phase-conjugate reflectivity is thought to be the result of the compound processes of FWM and SPBS, which will be discussed in the following section. Finally, in region (D), stable SPBS phase conjugation was achieved without any periodic behavior observed in phase-conjugate reflectivity. In this region, phase-conjugate reflectivity, laser output power, and laser wavelength all became stable. Phase-conjugate reflectivity was approximately 50%, and laser output power increased approximately 1.3 times that without the external phase conjugator. The spectral width was narrowed to below the resolution limit of the optical spectrum analyzer. An accurate spectral width, measured by the monitor etalon, was 7.2 pm. Figure 2b shows the Fabry–Pérot pattern of the AlGaInP diode laser coupled to the SPBS conjugator. In addition to the spectral-width narrowing, the laser wavelength was successfully stabilized in region (D) without any of the self-frequency scanning observed in previous work [11, 17, 18]

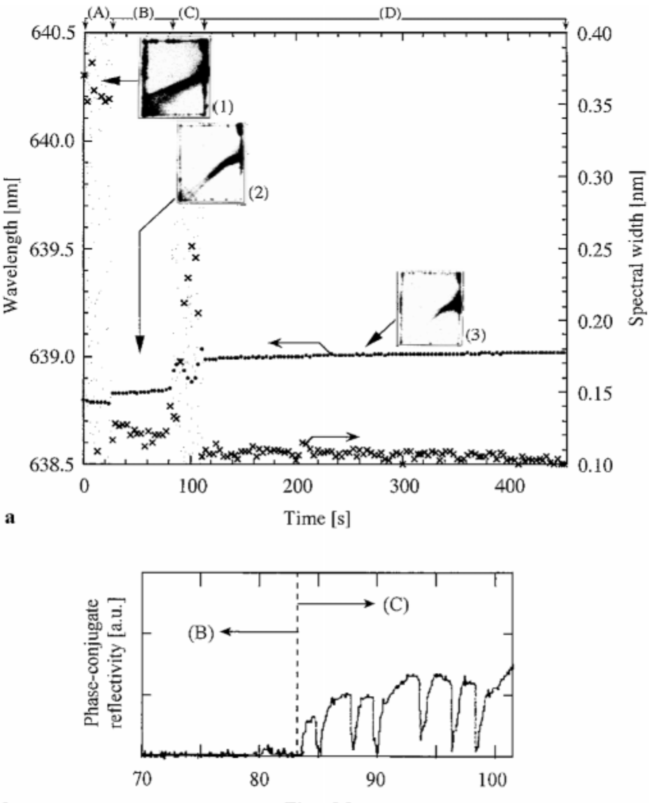

Fig. 3. a Temporal evolution of the laser wavelength (●) and spectral width (×) of the AlGaInP diode laser with the $BaTiO_3$ phase conjugator. The laser beam is incident on the crystal at $t = 0$. Note that the spectral width in region (D) is narrower than the resolution limit of the optical spectrum analyzer (~ 0.1 nm). Accurate measurement is done with a monitor etalon as described in the text. Photographs (1)–(3) show the optical paths in the $BaTiO_3$ phase conjugators in regions (A), (B), and (D), respectively. **b** The temporal evolution of phase-conjugate reflectivity in regions (B) and (C)

3 Discussion

3.1 *Spectral-width narrowing*

In the diode laser coupled to a phase conjugator, the laser spectral linewidth is determined by the spectral bandwidth of the refractive index grating induced in the photorefractive crystal. In the previous work that reported diode lasers coupled to a cat conjugator, the spectral bandwidth of the transmission grating self-formed in the cat conjugator was approximately 1 nm, which in turn determined the spectral width of the diode laser [9, 10]. For the $2k$ gratings formed in the SPBS conjugator, the diffraction efficiency is given by [24]

$$\eta = \frac{|\kappa| \sinh^2 sL}{s^2 \cosh^2 sL + \left(\frac{\Delta\beta}{2}\right) \sinh^2 sL} , \tag{1}$$

where κ is the coupling coefficient, L is the interaction length, $\Delta\beta$ is the momentum mismatch, and $s = |\kappa|^2 - (\Delta\beta/2)^2$. The spectral bandwidth of the $2k$ gratings $\Delta\lambda_{2k}$ can be obtained from the above equation. If we assume the interaction length L of a few millimeters in our phase conjugator, and the modulation depth of the index grating n_1 of $\sim 10^{-5}$ [25], $\Delta\lambda_{2k}$ is of the order of 10^{-11} m. This value is two orders of magnitude smaller than that given by the cat conjugator, which leads to the narrower spectral linewidth of the diode laser in our experiment.

Vahala et al. observed single longitudinal mode oscillation of < 100 kHz in a diode laser with a phase conjugator [8], whereas we observed much longer linewidth of 7.2 pm, corresponding to 5.3 GHz. This difference might come from the different methods used to measure the linewidth in [8] and our experiment. Vahala et al. used a self-heterodyne system, whereas a Fabry–Pérot. solid etalon was used in our experiment, which gives larger effective linewidth values because the detection system also measures changes in the center frequency of the diode laser

In previous work on the index-guided diode laser coupled to a ring conjugator [7] or a cat conjugator [9], spectral performance characteristics were made worse by the external conjugator: the optical spectral structure of the laser was several modes compared with near-single-mode operation without the external phase conjugator. This can be explained as the effects associated with the submodes in the photorefractive ring cavity [7] or the spectral bandwidth of the cat conjugator [9]. In our experiment, it should be noted that the SPBS conjugator forms no photorefractive resonator [26], and the spectral bandwidth is much narrower than that formed by the cat conjugator, as described above, which results in the narrow spectral-linewidth operation shown in Fig. 2b.

3.2 *Wavelength-stable oscillation*

With the SPBS conjugator, we have successfully stabilized laser wavelength without self-frequency scanning. Although the cause of self-frequency scanning was not explained in the previous work [11], scanning was shown not to be due to the accumulation of the frequency shift of the phase-conjugate wave observed in the phase-conjugator coupled dye laser [17, 18]. From the fact that self-frequency scanning is induced by the FWM conjugators [11, 17, 18] and is suppressed by the SPBS conjugator in our experiment, it is worth noting that the FWM process plays an important role in self-frequency scanning.

For non-scanning oscillation, an important technical issue is to keep the SPBS process stable, as shown in region (D) in Fig. 3. However, stability of the SPBS process proved sensitive to geometry, such as incident angle and position of the laser beam. As one example, temporal evolution of phase-conjugate reflectivity is shown in Fig. 4a, where the incident angle was slightly changed; periodic behavior persisted, and no stable SPBS process was observed. A question is, Why does the SPBS process revert suddenly to the FWM process? One possible explanation is competition between two different types of gratings, transmission gratings in the FWM process and $2k$ gratings in the SPBS process [27]

The geometry shown in the inset of Fig. 1 is only one way of obtaining stable SPBS phase conjugation. Another possible geometry is the $-c$ face incidence [23], where no cat conjugation can occur. We have not succeeded in obtaining a phase-conjugate wave in this geometry, despite our having observed phase-conjugate reflectivity of approximately 40% in the same geometry in a preliminary experiment with an He−Ne laser. The failure of the combination of the AlGaInP diode laser and the $-c$ face incidence geometry to generate a phase-conjugate wave will be investigated further.

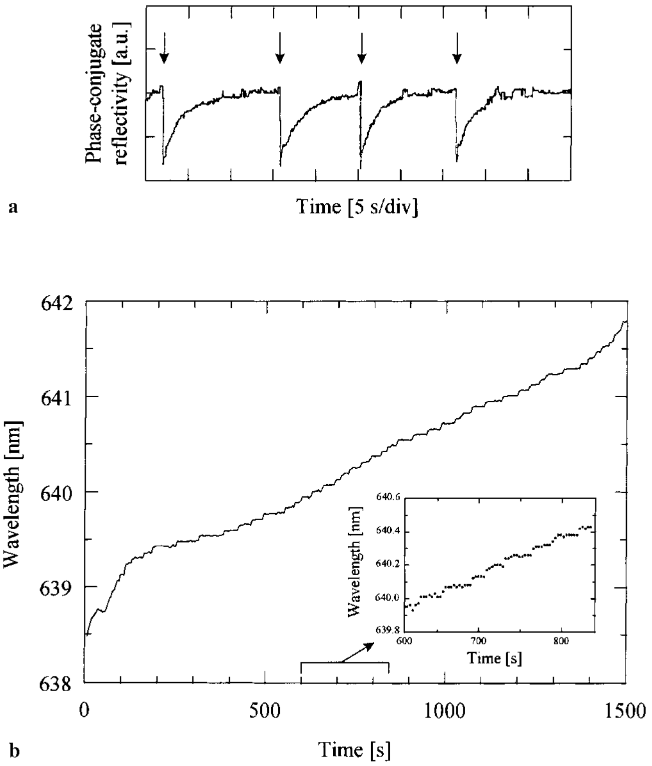

Fig. 4. a Temporal evolution of phase-conjugate reflectivity in the geometry where the incident angle of the laser beam is slightly changed from that in Fig. 3. **b** The corresponding temporal evolution of the laser wavelength. The precise transition of the laser wavelength is shown in the inset

Figure 4b shows the time evolution of the laser wavelength while periodic behavior, shown in Fig. 4a lasts. Under these conditions, the laser wavelength scans towards the red over the total gain bandwidth of the diode laser. This frequency scanning is similar to the self-frequency scanning reported previously [11, 17, 18]; however, the laser wavelength does not scan continuously, but the scanning is the accumulation of the small frequency hopping as shown in the inset of Fig. 4. Because the frequency hopping occurs when the process changes from SPBS back to FWM, indicated by the arrow in Fig. 4a, it is evident that the frequency hopping results from the FWM process, that is, from the mode hopping between longitudinal mode in the external phase-conjugate resonator and longitudinal mode in the photorefractive resonator formed in the self-pumped phase conjugator [28]. Vahala et al. also observed mode hopping in a diode laser coupled to a “ring” phase conjugator [8]. Thus, the FWM process plays a very important role in self-frequency scanning, and our result might explain the cause of the previously observed self-frequency scanning, attributable to the accumulation of very small mode hopping in the compound resonator which could not be identified by the interferometric method [11].

4 Conclusion

With an index-guided AlGaInP diode laser oscillating in the 639-nm region and a photorefractive $BaTiO_3$:Co crystal, we have demonstrated wavelength-stable, narrow spectral linewidth operation of a cw diode laser coupled to a phase conjugator. With the combination of the short wavelength laser source and the highly doped $BaTiO_3$:Co crystal, phase conjugation was induced by mean of the SPBS process with reflectivities up to 50%. With this phase conjugator, the spectral width was reduced to 7.2 pm due to the narrow spectral bandwidth of the $2k$ grating. In addition, self-scanning of the laser frequency has been successfully suppressed, and wavelength-stable oscillation has been demonstrated.

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