Invited Paper

A tunable external cavity laser diode with no mechanical movement

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ABSTRACT

An external-cavity laser diode that performs static wavelength scanning is proposed. It eliminates problems such as repeatability and tuning rate that arise due to mechanical movements induced in the external cavity of conventional systems because it requires no mechanical elements. Experiments have revealed that the scanning range and tuning rate are 1.3 nm and 1 kHz, respectively.

Keywords: wavelength scanning, external cavity; laser diode

1. INTRODUCTION

Wide-range wavelength scanning is one of the key techniques to improve the performance of optical devices such as spectroscopic instruments, optical coherence tomography system, and interferometers. Generally, wide-range wavelength scanning can be carried out by using a wavelength-selective element such as a diffraction grating and a tuning mirror with a gain medium[1]. Since the cavity of a laser diode (LD) is compact and susceptible to the external cavity, it is favorable for use as a gain medium[2]. In particular, if an output facet of the LD is processed with an antireflection (AR) coating, the LD is strongly coupled to the external cavity[3-5]. Tiziani proposed a Littman-cavity-based light source that provided a continuous wavelength tuning range of 25 nm by using an AR-coated LD[6]. A tuning range of 4 nm was obtained with an intracavity glass plate as the fine tuning device and an AR-coated 633-nm LD in the Littrow configuration[7].

In particular, since the output facet of the commercially available, conventional LD has been processed with an AR coating, the cavity of the LD can be coupled to an external cavity easily as it is. Harvey proposed an external-cavity laser diode (ECLD) that consists of a commercial LD in the Littman configuration; the tuning range of this LD was greater than 20 nm[8]. We have proposed a simple Littman-type ECLD capable of stabilizing the wavelength through a feedback control[9] and a Littrow-type ECLD for laser cooling and trapping[10]. Standard LDs are used in these configurations.

However, we need to focus on the repetition rate, repeatability, tuning speed, and temporal stability of wavelength scanning because ECLDs usually induce mechanical movements that can affect the optical alignment and piezoelectric transducers (PZT) that have hysteresis characteristics. These movements affect the robustness of the cavity and the hysteresis deteriorates the repeatability. The repetition rate and tuning speed were limited by the mechanical movements. To overcome these problems, an electro-optical arrangement was set up in the Littrow configuration[11, 12]. In Ref. 11, an electro-optical crystal was inserted into the cavity instead of mechanically moving the grating. The electric field applied to the crystal changes the refractive index, which in turn tunes the wavelength. The tuning range and tuning speed of this system were 0.01 nm and 3×10^{-3} nm/μs, respectively, with the special AR-coated LD. Although the system is simple, the tuning range is small. The combination of a liquid crystal cell and a $LiNbO_3$ crystal is used in the external cavity in Ref. 12, in which a tuning range of 10.3 nm was obtained.

In this paper, we propose another type of ECLD that consists of an acousto-optical element instead of an electro-optical crystal. As our system also requires mechanical movements to be restricted, static wavelength scanning can be carried out; thus, the problems arising from the mechanical movements are resolved.

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2. PRINCIPLE

Generally, wide-range wavelength scanning can be carried out with the configuration shown in Fig. 1(a), in which a mechanical rotating mirror driven by a PZT is used. The fundamental equation in Fig. 1(a) is represented by[13]

$$\lambda = d(\sin\theta_i + \sin\theta_d) \quad (1)$$

where λ is the wavelength, d is the groove spacing, and θ_i and θ_d are the incident and diffraction angles, respectively. When the incident angle is constant, the wavelength varies as given by

$$\Delta\lambda = d[\sin(\theta_d + \Delta\theta_d) - \sin\theta_d] \quad (2)$$

depending on $\Delta\theta_d$, which is the change in the diffraction angle.

Our proposed system is shown in Fig. 1(b): as seen in the figure, wavelength scanning is controlled by the incident angle, while the diffraction angle is constant. The scanning is accomplished statically because an acousto-optic deflector (AOD) is used for the incident angle control. In this case, the wavelength change $\Delta\lambda$ is given by

$$\Delta\lambda = d[\sin(\theta_i + \Delta\theta_i) - \sin\theta_i] \quad (3)$$

Thus no mechanical movement is required in our system.

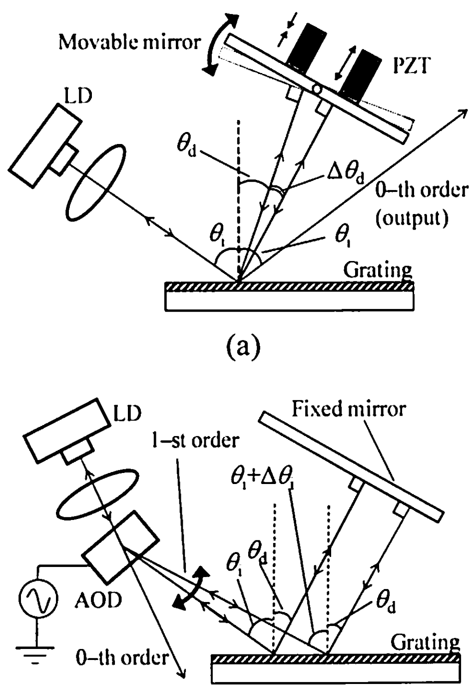

Fig. 1. Schematic of (a) the conventional ECLD and (b) the proposed system.

3. EXPERIMENTS

We demonstrated both a mechanical wavelength scanning (Fig. 1(a)) and a static one (Fig.1 (b)) so as to compare the characteristics between them. Also a standard LD and an AR-coated LD are used respectively in these experiments to investigate the scanning range depending on the light source.

3.1 Demonstration of the mechanical wavelength scanning

Schematic of the experimental setup is illustrated in Fig. 2. We used two kinds of LD, LD1 (a commercial LD having an AR-coated facet, λ_0 = 658 nm, P_{max} = 80 mW) and LD2 (a special AR-coated LD, λ_0 = 636 nm, P_{max} =5 mW), in the experiments, where λ_0 and P_{max} are the central wavelength and maximum output power, respectively. The changes in the temperature of the LD were restricted to deviations of ±0.01°C by means of a Peltier thermo-controller. The output beam from the LD is collimated with a microscope objective lens. The radiated beam from the LD passes through the polarizing beam splitter (PBS). The stronger s-polarized beam is used to form the ECLD. The passing p-polarized beam is fed into the optical spectrum analyzer (OSA) to monitor the spectra. Since the first-order beam diffracted by the grating is reflected on the mirror and fed back to the LD, the oscillating wavelength is strongly affected by the external cavity. The groove spacing of the holographic diffraction grating and initial incident angle θ_i were 1/1800 mm and ~70°, respectively. The mirror was driven by a couple of PZT. The results observed in LD1 are shown in Fig. 3. The scanning range of 2 nm was obtained with the mechanical rotation of the mirror. A part of Fig. 3 is extracted and magnified in Fig. 4. The equal interval of 0.06 nm was observed in this wavelength scanning. This interval is due to the resolution of the OSA.

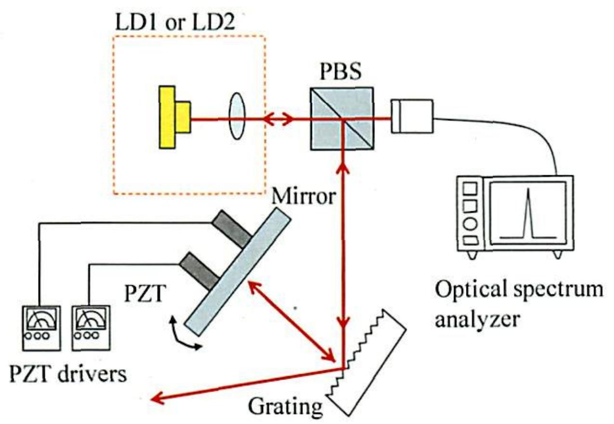

Fig. 2. Schematic of the mechanical wavelength scanning system.

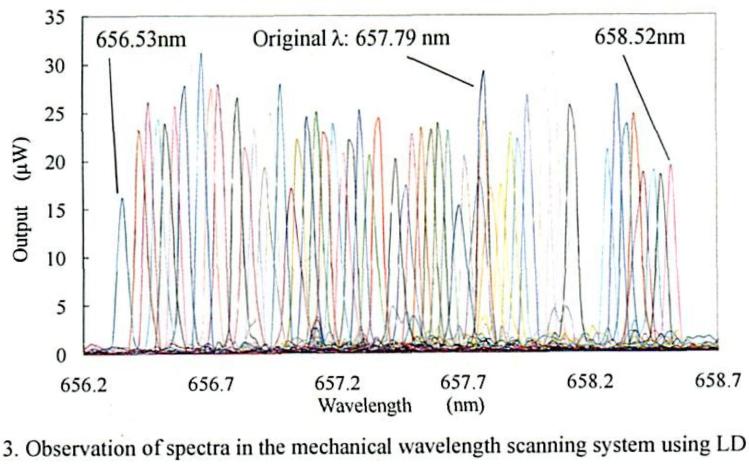

Fig. 3. Observation of spectra in the mechanical wavelength scanning system using LD1.

Next, we replaced LD1 with LD2 and observed the spectra. When we interrupt the beam reflected by the PBS, sharp spectra were not observed as shown in Fig. 5(a) because the AR-coating inhibits the laser oscillation between the facets of the LD chip and the external cavity was uncoupled. While the interruption was removed and the external cavity was coupled to the LD, discriminative spectra were observed as shown in Fig. 5(b). The scanning range of 1.3 nm was obtained according to the rotation of the mirror. No clear spectra were observed outside of the region shown in Fig. 5(b) because the intensity of the diffraction beam decreases and the coupling between the LD and external cavity is collapsed.

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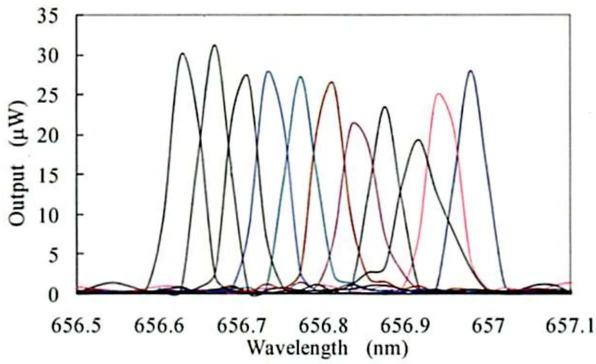

Fig. 4. Observation of a part of spectra extracted from Fig. 3.

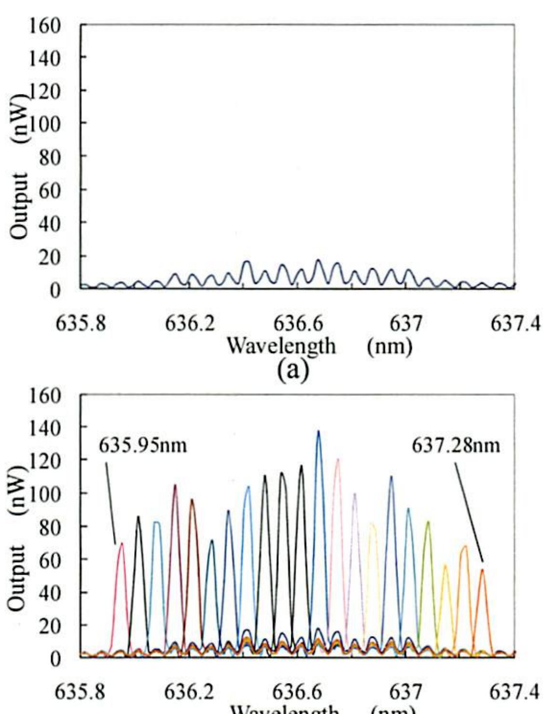

Fig. 5. Observed spectra of LD2 in (a) free running state and (b) in the mechanical wavelength scanning system.

3.2 Demonstration of the static wavelength scanning

We demonstrate a wavelength scanning by use of AOD. The experimental setup is shown in Fig. 6. The AOD is inserted in the optical path of the ECLD that is shown in Fig. 2. We used the same LDs that are used in the experiments described in Sec. 3.1. The mirror was fixed to realize the static scanning. The diffraction angles were ~18° and ~15° for LD1 and LD2, respectively, under the initial incident angle of ~63°.

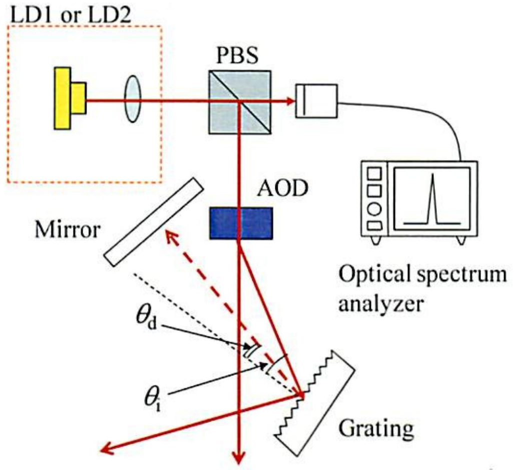

Fig. 6. Schematic of the static wavelength scanning system.

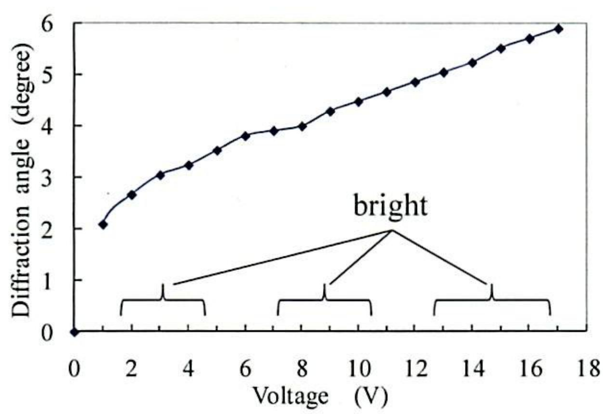

Fig. 7. Observed diffraction angle in the AOD corresponding with the control voltage.

Observations of the diffraction angle of the AOD are plotted in Fig. 7. The central frequency of the acoustic wave is 75 MHz. The diffraction angle increases linearly and it varies by 0.18°/V with the control voltage. Also we observed that the intensity of the diffraction beam varied periodically according to the control voltage as indicated in Fig. 7.

First, we demonstrated a wavelength shift by use of LD1. When the control voltage applied to the AOD was varied from 13.0 V to 16.2 V, the wavelength shift was observed as shown in Fig. 8. The solid line shows the theoretical calculation using Eq. (3). Stable spectra were observed in the region from 659.5 nm to 658.8 nm in the lower-control-voltage area (13.0 V – 13.9 V) and in the region from 657.8 nm to 656.7 nm in the higher-control-voltage area (14.8 V – 16.2 V). No stable spectra were observed in the middle range of the control voltage because the power of the deflected beam decreased considerably in this region, and the oscillation mode could not be coupled to the external cavity. However, in the lower and higher voltage areas, tuning ranges of 0.7 nm and 1.1 nm were observed. It was determined that the wavelength scanning rate was 0.78 nm/V. Traces of the observed spectra are shown in Figs. 9(a) and 9(b) in the lower and higher voltage areas, respectively. The interval of these spectra was ~0.04 nm.

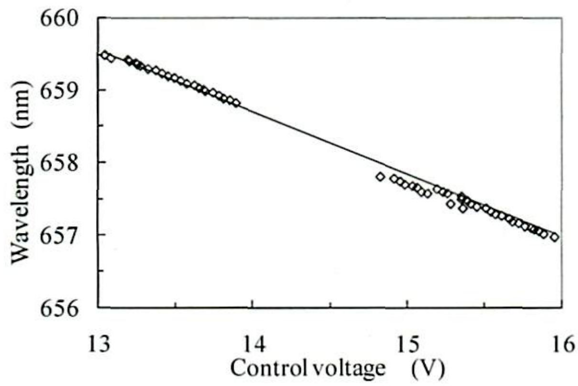

Fig. 8. Wavelength shift in the static wavelength scanning system using LD1. The solid line is the theoretical calculation of the shift.

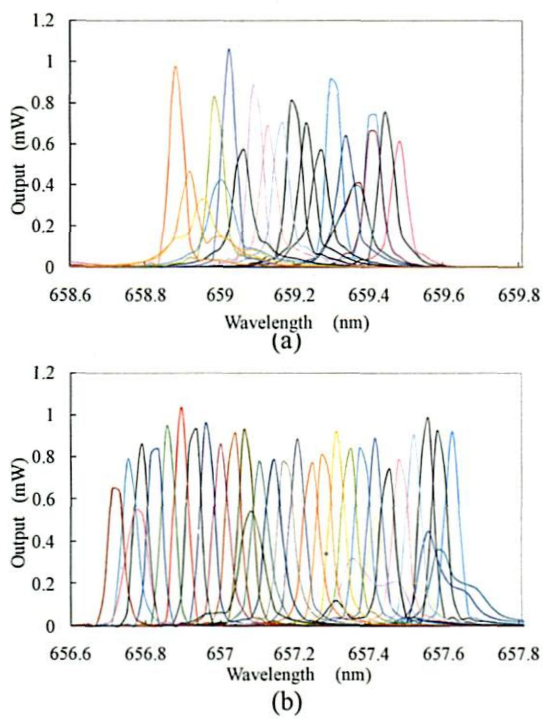

Fig. 9. Spectra observed in (a) the lower and (b) the higher voltage area in the static wavelength scanning system using LD1.

Next, we observed the spectra with LD2. The LD showed the multimode oscillation and no clear spectra were observed as shown in Fig. 10(a), when the external cavity was not coupled to LD2 with the interruption of the feedback beam. When we clear the optical path from the interruption, however, discriminative spectra were observed according to the tuning of AOD's control voltage. The scanning range of the wavelength was 0.74 nm as shown in Fig. 10(b), in this demonstration.

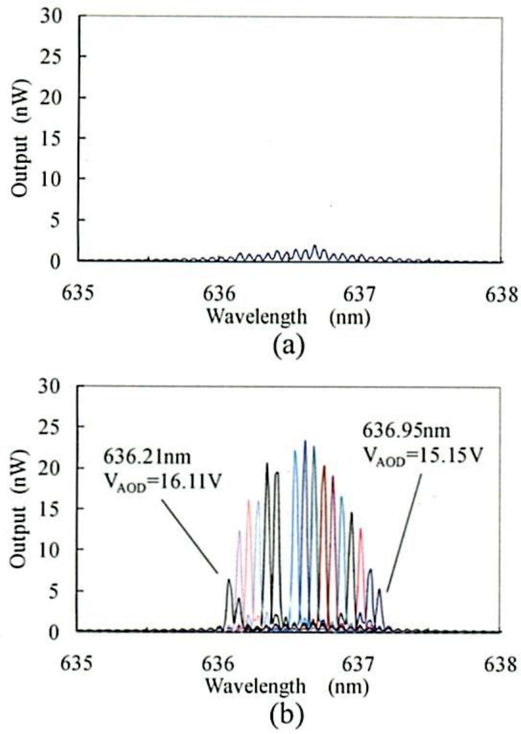

Fig. 10. Observed spectra of LD2 in (a) free running state and (b) in the static wavelength scanning system.

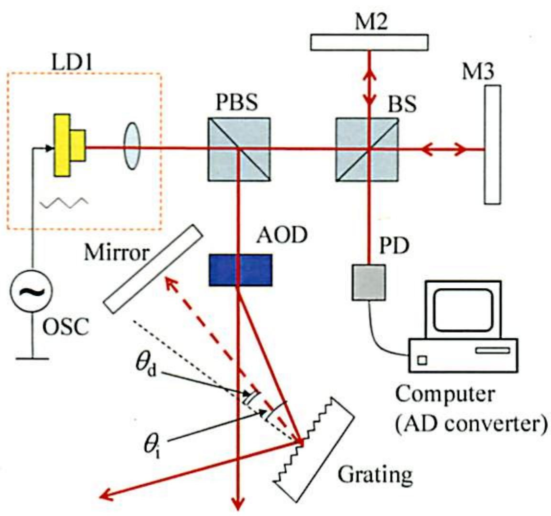

Fig. 11. Experimental setup for observing the modulating interference signal.

3.3 Demonstration of the phase modulation in an interferometer

In applications such as spectroscopic instruments, optical coherence tomography, and interferometer, continuous wavelength scanning and tuning speed are important characteristics. We observed an interference signal by using the static ECLD to confirm these important characteristics. We used LD1 as a light source and a conventional Twyman-Green-type interferometer whose optical path difference is ~1 mm as shown in Fig. 11. In this unbalanced interferometer, direct phase modulation can be achieved with a wavelength-scanning light source[14]. When triangular wavelength scanning was employed as shown in Fig. 12, we observed a continuous interference signal that exhibits partially sinusoidal waveform in the linear region of the triangular wave. The modulation frequency in Figs. 12(a), 12(b), and 12(c) were 100 Hz, 300 Hz, and 1 kHz, respectively, and we were able to observe a stable interference signal in these frequencies. The modulation depths in the interference signal were almost constant up to 1 KHz. Since the amplitude of the triangular control voltage was 0.5 V, the change in the wavelength of the linear part is estimated to be 0.78 nm from the wavelength-scanning rate, as discussed earlier. This observation of the interference signal confirms that continuous and high-speed wavelength scanning is possible using our system.

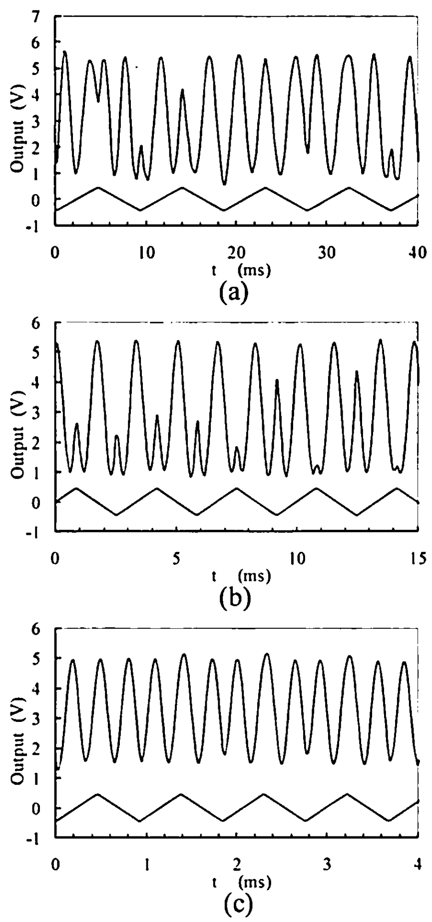

Fig. 12. Traces of the interference signal and triangular modulating signal employing frequency of (a) 100 Hz, (b) 300 Hz, and (c) 1 kHz.

4. DISCUSSION

The maximum wavelength tuning range was 2 nm in the mechanical scan and 1.1 nm in the static scan, respectively, in our demonstration. Both are observed in the ECLDs that uses standard LD as a light source. The scanning rang of 1.3 nm and 0.74 nm obtained by the special AR-coated LD are rather smaller than we expected. A possible interpretation of these results is that the intensity of the feedback beam is too weak to couple the LD with the external cavity. However, several demonstrations confirm that the proposed system functions as the wavelength scanning source. The observations of the phase modulation in the interference signal indicate that many advantages, such as continuous, stable, and high rate of wavelength scanning, are obtained in the proposed system. If a special AR-coated LD which radiates high-power beam is available, wider wavelength tuning range would be realized with our system.

5. CONCLUSIONS

We have proposed and demonstrated a static type of wavelength-scanning ECLD. Wide range and continuous wavelength scanning can be carried out under a high tuning rate. We will attempt to demonstrate wider wavelength tuning by incorporating high-power AR-coated LD to the static wavelength scanning system.

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