

# Dual-color operation of a laser diode under current and temperature control

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We describe a novel method that operates a laser diode with dual colors. Our system requires no external optical parts but does require current and temperature control. We can use either a single color on a time-sharing basis or dual colors simultaneously. The difference between the wavelengths is  $\sim 0.6$  nm, which is as much as 10 times that generated by current control alone. Temporal stability of the generated two wavelengths and the response time of the wavelength change were confirmed through a number of experiments. © 2003 Optical Society of America

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## 1. Introduction

Laser diodes (LDs) have been widely used to construct various types of compact interferometers, because wavelength tunability enables us to modulate the wavelength easily. When the object's surface roughness is larger than a half-wavelength, a two-wavelength interferometer<sup>1</sup> (TWI) provides an unambiguous measurement of the phase.

By their very nature, TWIs require two wavelengths. If separate two LDs are used, however, optical axes are difficult to adjust and the optical setup itself becomes fragile for disturbance. Quasi-TWIs (QTWIs), which use only one LD, have been proposed<sup>2,3</sup> as a means of sidestepping the problem. With QTWIs, two wavelengths are generated by varying the dc bias current injected into the LD on a time-sharing basis. Under such tight control, however, the difference in the QTWIs' wavelengths is minimal, resulting in a few centimeters of synthetic wavelength. Thus it is difficult to improve the measurement accuracy, because the synthetic wavelength is very large.

The LD wavelength's dependency on the injection current is shown schematically in Fig. 1. The wavelength increases with increasing injection current accompanied by a phenomenon we refer to as "mode

hop," which is shown in the region from  $I_1$  to  $I_2$  in Fig. 1. Within a current range from  $I_2$  to  $I_3$ , the wavelength linearly increases from  $\lambda_2$  to  $\lambda_3$  with the injection current at a rate of  $\beta_C$ , where  $\beta_C = \Delta\lambda/\Delta I$  is a current-modulation efficiency.  $\beta_C$  has been previously estimated<sup>4,5</sup> as  $4\sim 6 \times 10^{-3}$  nm/mA. Because the difference between currents  $I_2$  and  $I_3$  is usually less than 10 mA, the wavelength-scanning range equals at most  $6 \times 10^{-2}$  nm. Moreover, such a large fluctuation in current inevitably affects the intensity of the LD output. This causes the interferometer to generate an erroneous measurement error.

On the other hand, two-color LD systems that use an external cavity have been reported.<sup>6,7</sup> Although the difference of the oscillating wavelength is rather large, adjustments of the optical axis are complicated. Additional optical parts such as a lens, a grating, and a mirror are required in such two-color light sources. The complication is similar to that of the light source that uses two separate LDs.

In this paper we describe and demonstrate a technique that operates a LD with dual wavelengths by use of a mode hop. To the best of our knowledge this is the first report on the dual-color operation of LDs for a TWI by use of the mode hop. Although the difference between the provided wavelengths is restricted in our technique, both the setup and the operation are very simple. This method can be easily applied to commercially available LDs. We can use either two wavelengths simultaneously or a selected single wavelength by use of a current control. Temporal stability of the generated two wavelengths and the response time of the wavelength change were confirmed through a number of experiments.

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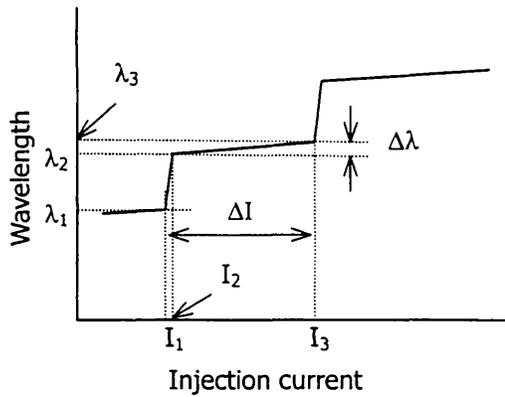


Fig. 1. Dependency of the LD's wavelength change on the injection current.

## 2. Principle of Operation and Fringe Generation

The dual-color system uses the feature shown in Fig. 1. As the wavelength of the LD varies with not only the injection current but also the atmospheric temperature, we control the temperature to eliminate the wavelength fluctuation of the LD. Under such temperature control, LD oscillates with  $\lambda_1$ , or  $\lambda_2$  or both  $\lambda_1$  and  $\lambda_2$ , depending on the injection current. Generally the difference between  $\lambda_1$  and  $\lambda_2$  is  $\sim 0.6$  nm, which is as much as 10 times that generated by the current control alone. The LD's output intensity varies little, however, in difference of this magnitude.

The interference fringes generated with each wavelength are respectively given by

$$S_i(x, y) = a_i(x, y) + b_i(x, y) \cos[2\pi f_i x + \alpha_i(x, y)] \quad (i = 1, 2), \quad (1)$$

where

$$\alpha_i(x, y) = 2\pi L(x, y) / \lambda_i \quad (2)$$

are the phases that depend on the wavelength and the optical pass difference (OPD)  $L$ ,  $f_i$  is the spatial frequency in the  $x$  direction.  $a_i(x, y)$  and  $b_i(x, y)$  are the dc term and the amplitude of the ac term, respectively, which are introduced by the nonuniformity of the light intensity. If the LD simultaneously radiates close two wavelengths, the spatial frequencies  $f_1$  and  $f_2$  become almost the same. Thus we can state  $f_1 = f_2 = f_0$ . Moreover, if the amplitude of each color is equal, the conditions  $a_1 = a_2 = a_0$  and  $b_1 = b_2 = b_0$  are also satisfied. Then we can observe the overlapped fringe image

$$S_1 + S_2 = 2a_0 + 2b_0 \cos \Delta\alpha \cos(2\pi f_0 x + \bar{\alpha}), \quad (3)$$

where

$$\Delta\alpha = 2\pi d / \Lambda \quad (4)$$

is the phase difference and  $\bar{\alpha} = (\alpha_1 + \alpha_2) / 2$  is the mean phase.  $d$  and  $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$  represent a half of the OPD and the synthetic wavelength, respectively. Coordinates  $(x, y)$  are omitted in the equations. The

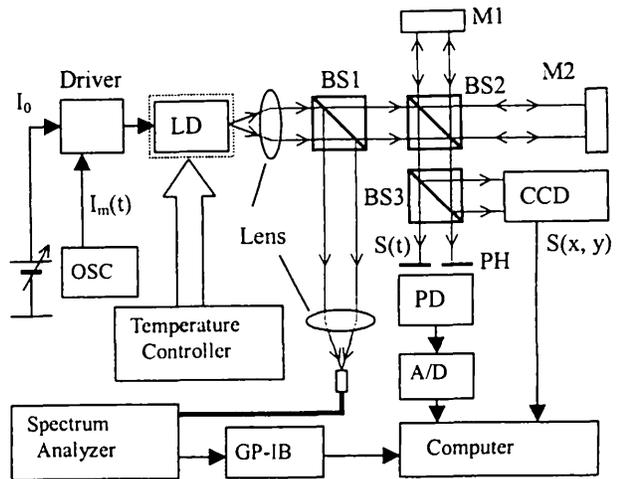


Fig. 2. Schematic of the experimental setup. OSC, oscillator; BSs, beam splitters; M, mirrors; PH, pin hole; A/D, analog-to-digital converter; PD, photodiode; CCD, CCD camera; GP-IB, general purpose interface bus.

visibility of the image represented by Eq. (3) is calculated by

$$\gamma_{12} = (b_0/a_0) \cos \Delta\alpha, \quad (5)$$

whereas the visibility of the single fringe represented by Eq. (1) is given by

$$\gamma_0 = b_0/a_0. \quad (6)$$

when the single wavelength is used. Equation (5) shows that the visibility deteriorates by the factor of  $\cos \Delta\alpha$  in the dual-color operation.

## 3. Experimental Setup

In the experimental setup shown in Fig. 2, bias current  $I_0$  and modulating current  $I_m(t)$  are injected into the LD. Fluctuation of the injection current was strictly controlled within 0.01 mA by the LD driver. The LD's temperature is held to within  $\pm 0.01$  °C with the temperature controller. Light radiated from the LD was fed into both an optical spectrum analyzer and a Twyman-Green interferometer that consisted of M1, M2, and BS2 (see Fig. 2). The OPD of the interferometer was 200 mm. Interference signal  $S(t)$  and image  $S(x, y)$  are detected by a photodiode (PD) and a CCD camera, respectively. The intensity of the spectrum,  $S(t)$ , and  $S(x, y)$  are processed by a computer. In this measurement, we used standard multiquantum well LDs whose wavelengths are 685 nm (LD1, Mitsubishi, ML1412R) and 785 nm (LD2, Hitachi, HL7851G), respectively.

## 4. Experimental Results and Discussion

### A. Observations of the Oscillation

We first measured the LD's wavelength dependencies on the injection current to search the mode-hopping point. Results are shown in Fig. 3; the temperatures were controlled at 22.8 °C and 17.2 °C, respectively, for LD1 and LD2, nearly room

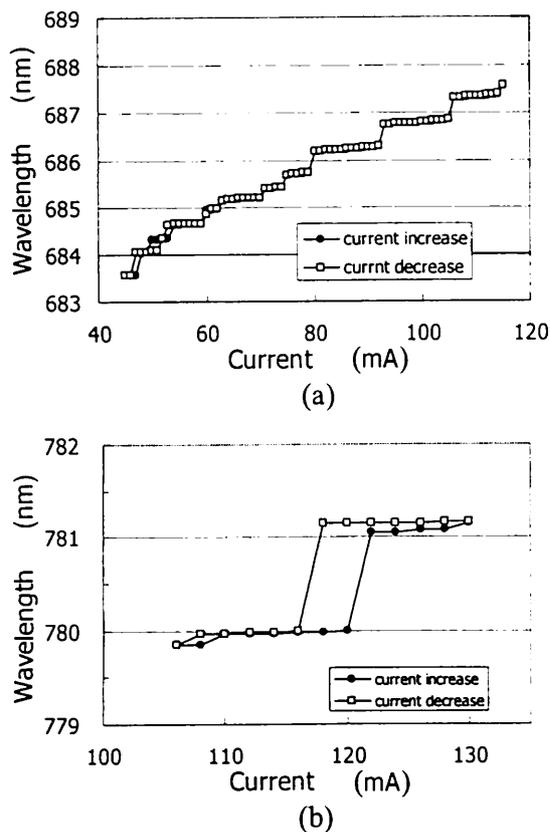


Fig. 3. Measured dependencies of the wavelength change of (a) LD1 (685 nm) and (b) LD2 (785 nm) on the injection current.

temperature. Although the wavelength of LD1 traces same loci both in increment and in decrement of the injection current over 60 mA, that of LD2 varies with the hysteresis. Distinctive spectra were not observed in Fig. 3(b) under 105 mA. We find that the mode hops occur at several injection currents in Fig. 3(a). We used LD1 at 22.8 °C in the following experiments.

Our technique is detailed in Fig. 4, the spectral intensities of LD1 under the current control are observed. Modulating current  $I_m(t)$  was held at zero during these observations. dc bias current  $I_0$  was controlled from 79 to 81 mA discretely. In the initial state, the dominant wavelength of 685.63 nm was observed at  $I_0 = 79$  mA, as shown in Fig. 4(a). When  $I_0$  increased by 0.4 mA, as shown in Fig. 4(b), another oscillation appeared at 686.18 nm, and the initial spectral component shrunk. We observed two major spectra corresponding to adjoining LD oscillation modes at  $I_0 = 80$  mA, as shown in Fig. 4(c). The wavelengths differed by 0.55 nm, and the intensity  $P_2$  at 686.18 nm came up to the level of  $P_1$  at 685.63 nm. In this case, our system provides the synthetic wavelength of  $\sim 855 \mu\text{m}$ . Furthermore, when we increased the injection current, the initial spectral component gradually disappeared and the other one dominated, as shown in Figs. 4(d) and 4(e). This clearly demonstrates the LD wavelength's susceptibility to even slight modulations in current. More-

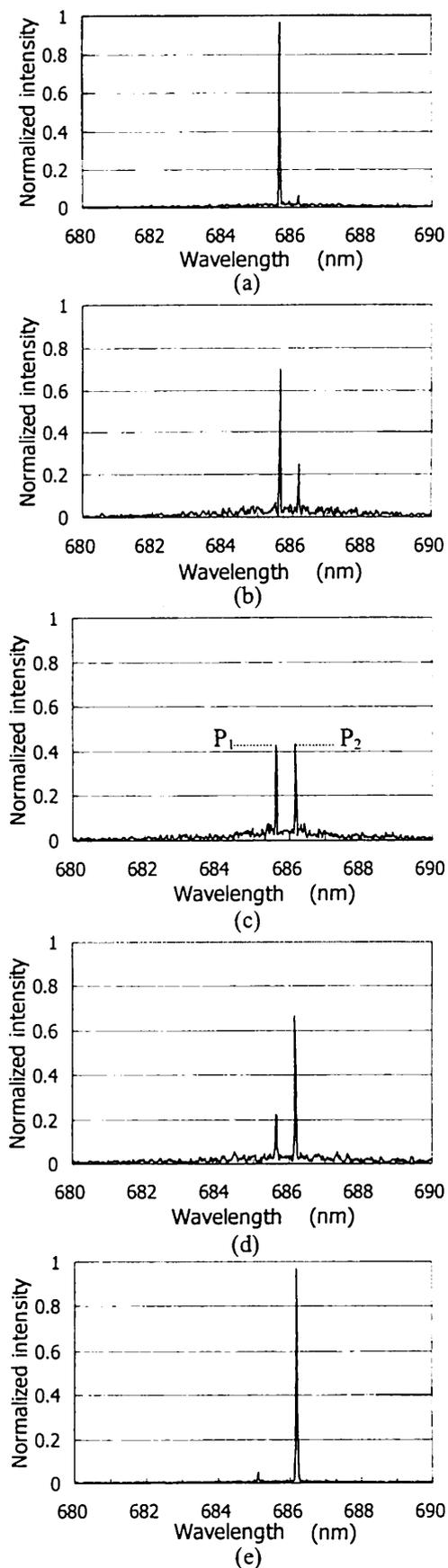


Fig. 4. Normalized spectral intensities observed at 22.8 °C. dc bias currents were (a) 79, (b) 79.4, (c) 80, (d) 80.6, and (e) 81 mA, respectively.

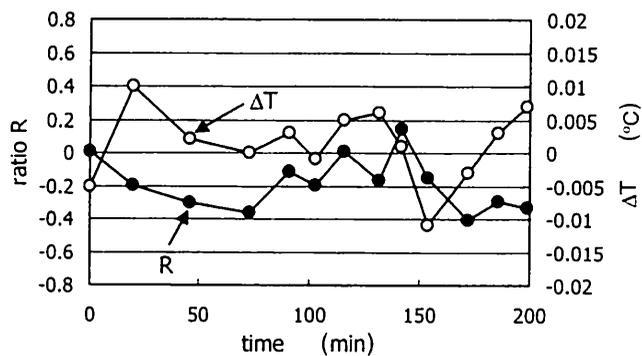


Fig. 5. Long-term observation of the deviations of controlled temperature and the intensity ratio between  $P_1$  and  $P_2$ .

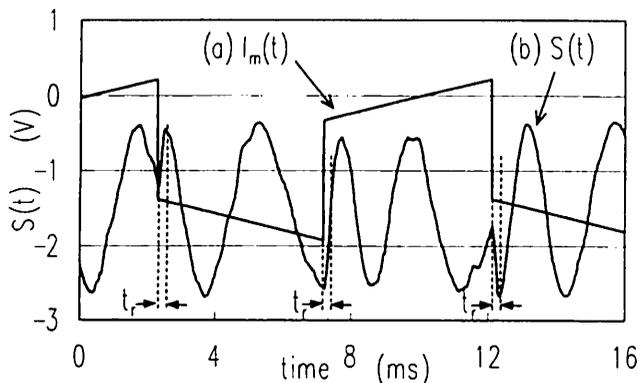


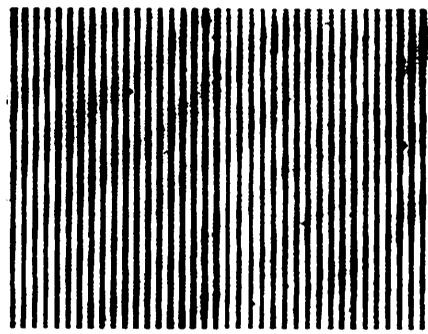
Fig. 6. Observations of (a) the modulating current  $I_m(t)$  and (b) the interference signal  $S(t)$ .

over, it indicates that the intensity ratio between both spectra varies with the injection current.

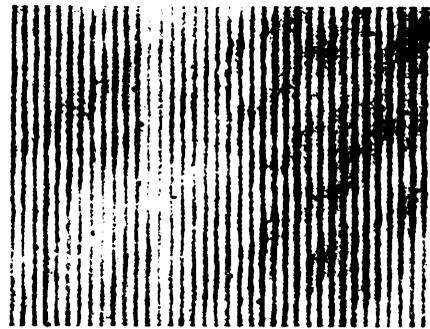
We measured the intensity ratios between  $P_1$  and  $P_2$  for 200 min after the data shown in Fig. 4(c) were observed to confirm the long-term stability of the dual-color operation. The ratio was evaluated by

$$R = (P_2/P_1) - 1. \quad (7)$$

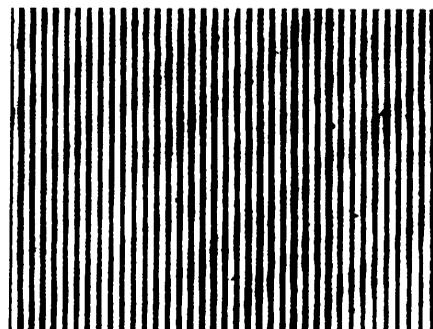
$R$  becomes zero when  $P_2$  is equal to  $P_1$ . At the same time, we monitored the deviations of the controlled temperature. Results are shown in Fig. 5. The LD's temperature has been held within  $\pm 0.01^\circ\text{C}$ . Although the variation of  $P_2$  ranged from  $-40\%$  to  $+10\%$  with respect to  $P_1$  in this observation, dual-color oscillations were maintained. If either of the intensities were detected, we can adjust  $R$  to be zero by use of a feedback control on the injection current. We also confirmed that the oscillations for major two states [Figs. 4(a) and 4(e)] were stable for a period of 6 h. The fact that we were able to realize the long-term stability of the LD oscillation by means of the strict temperature and current controls proves that we can use two different wavelengths for a measurement at the same time or on a time-sharing basis. The difference between the two wavelengths is as much as 10 times that obtained by the current control alone in the linear regions, as seen in Fig. 1. Thus our proposed system provides a stable synthetic



(a)



(b)



(c)

Fig. 7. Interference fringes observed at (a) 79, (b) 80, and (c) 81 mA.

wavelength smaller than 1 nm. This system allows us to improve the measurement accuracy in the QTWI. The same phenomenon of the dual-color oscillation was not observed at any dc bias current in LD2, because of the wavelength's hysteresis on the injection current.

#### B. Response Time of the Wavelength Shift

We injected the combined modulating signal  $I_m(t)$  that is composed of the triangular and the rectangular signals whose amplitudes are 0.4 and 1.0 mA, respectively, into the LD to confirm the response time for the wavelength change. The interference signal  $S(t)$  reflects sinusoidal changes at the linear slope of  $I_m(t)$ , as shown in Fig. 6. The phase of the interference signal changes rapidly without disorder at the leading and the trailing edges of the discontinuity in  $I_m(t)$ . This observation shows that the wavelength

change can be accomplished just as quickly by simply adjusting the dc level of the injection current. The response time  $t_r$ , shown in Fig. 6 is estimated to be 0.2 ms. This rapid change in wavelength allows us to perform the immediate signal processing in the QTWI on a time-sharing basis.

### C. Fringe Observations under the Dual-Color Operation

We observed the interference fringe  $S(x, y)$ . The images shown in Fig. 7 were observed at  $I_0 = 79, 80,$  and  $81$  mA, respectively, which correspond to the dc levels for observing Figs. 4(a), 4(c), and 4(e). When bias current  $I_0$  was controlled to 79 and 81 mA, clear fringes were observed, as shown in Figs. 7(a) and 7(c), respectively, because one of the two spectra became dominant by the current control. The spatial periods in both fringes were almost same as those mentioned in Section 2. While  $I_0$  was set to 80 mA, the captured image was blurred, as shown in Fig. 7(b). As the intensities of both spectra were the same at  $I_0 = 80$  mA, as shown in Fig. 4(c), the fringe shown in Fig. 7(b) was formulated by Eq. (3). Thus the deterioration of the visibility is introduced by the phase difference between Figs. 7(a) and 7(c). This deterioration, for instance, is applicable to the displacement measurement, because the factor  $\cos\Delta\alpha$ , which is concerned with the OPD, is derived from visibilities  $\gamma_0$  and  $\gamma_{12}$ . If  $\gamma_0$  is measured once for a single wavelength, we can calculate the displacements from only the overlapped fringe image represented by Eq. (3).

### 5. Conclusions

In conclusion we demonstrated the simplest possible way to conduct dual-color operation in a LD. Our method requires no external optical parts but does require current and the temperature control. The system we proposed provides either a single color on

a time-sharing basis or dual colors simultaneously. Although the change in the wavelength is discrete during single-color operation, the difference in the wavelengths generated is 10 times that generated by the conventional current control alone. And, because these wavelengths are generated by only the slightest dc changes in current, the LD's output power is minimal. We have confirmed the wavelength's temporal stability as well as the response time of the wavelength shift. A possible technique for a displacement measurement is proposed through the observations of the interference fringes. A small and stable synthetic wavelength allows us to improve the measurement accuracy in the QTWI. We plan to use such a system to perform the long range of displacement measurement in future research.

### References

1. A. J. den Boef, "Two-wavelength scanning spot interferometer using single-frequency diode lasers," *Appl. Opt.* **27**, 306–311 (1988).
2. C. C. Williams and K. Wickramasinghe, "Optical ranging by wavelength multiplexed interferometry," *J. Appl. Phys.* **60**, 1900–1903 (1986).
3. T. Suzuki, O. Sasaki, and T. Maruyama, "Absolute distance measurement using wavelength-multiplexed phase-locked laser diode interferometry," *Opt. Eng.* **35**, 492–497 (1996).
4. K. Tatsuno and Y. Tsunoda, "Diode laser direct modulation heterodyne interferometer," *Appl. Opt.* **26**, 37–40 (1987).
5. Y. Ishii, J. Chen, and K. Murata, "Digital phase-measuring interferometry with a tunable laser diode," *Opt. Lett.* **12**, 233–235 (1987).
6. Y. Sidorin and D. Howe, "Laser-diode wavelength tuning based on butt coupling into an optical fiber," *Opt. Lett.* **22**, 802–804 (1997).
7. J. Struckmeier, A. Euteneuer, B. Smarsly, M. Breede, M. Born, M. Hofmann, L. Hildebrand, and J. Sacher, "Electronically tunable external-cavity laser diode," *Opt. Lett.* **24**, 1573–1574 (1999).