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**6. AUTHOR(S)**
Jin Hyuk Kwon, Do Hoon Kim, Gregory Schuster, and Ja H. Lee

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
NASA Langley Research Center
Hampton, VA 23665-5225

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## Abstract

An experiment on the phase stability of an injection-locked beam was done by using AlGaAs semiconductor lasers. The coherence of two beams from master and slave lasers was measured by interference between the beams in the Twymann-Green interferometer. The phase change of the output beam of the slave laser as a function of the driving current was measured in a Mach-Zehnder interferometer consisting of the master and slave lasers, and a value of 2.5 radians/mA was obtained.

## Introduction

The improvement of AlGaAs crystal growth technology and the new laser cavity configuration have enabled the rapid development of room-temperature-operated, high-power semiconductor lasers. Recently, the laser diode array (LDA) has achieved 38 W continuous wave (CW) output power (ref. 1), while a single stripe semiconductor laser did not exceed an output power of more than 100 mW. Most of the LDA's developed earlier had shortcomings—such as a widely distributed spectrum and an uneven spatial distribution of amplitude—and are perhaps adequate only for pumping solid-state lasers. Accordingly, to overcome these shortcomings, continuous efforts have been poured into the development of room-temperature-operational, high-power, diffraction-limited LDA's (ref. 2).

The applications of the LDA are divided into two categories: (1) spectroscopy and coherent transmission require a narrow bandwidth of the output laser beam and (2) solid-state laser pumping, beam combining, manufacturing, and beacon beams generally require high-power output. The increase in beam power of a single laser diode array has a limit, so beam combining is necessary to obtain a high-power output (refs. 3 and 4). The output-power improvement in a single-chip base is achieved either by phase coupling the evanescent wave between parallel cavity stripes or by phase coupling Y-junction arrays (ref. 5). However, the power from a single-chip diode seems to be limited to only tens of watts; hence, high-power output beyond that of a single chip requires the combination of a master oscillator and power amplifier (MOPA) diode system. The beam from the master oscillator is split into several beams, and then the split beams are fed into every amplifier diode element simultaneously. Mutual coherence of the beams from the amplifier array is important and achieved either by injection-locking or by traveling-wave amplification (refs. 6 and 7). The injection-locking amplifier (ILA) has a narrow gain bandwidth (in a magnitude of GHz) but has the advantage of low noise and high amplification with a simple system configuration. On the other hand, the traveling-wave amplifier (TWA) has a wide gain bandwidth (in a magnitude of THz) but also has a slightly noticeable drop in power extraction efficiency. Manufacturing requirements are also more stringent for the TWA, as a thin-film facet coating is required to reduce the reflectivity to the order of 1 percent.

In the experiments, the variability of the degree of interference and phase stability of the ILA, which are the important factors for beam combining, was studied. The variation in driving current of a semiconductor laser causes changes in electron density and temperature. These changes eventually cause the refractive index to change and give rise to an effect similar to cavity-length variation (refs. 8 and 9). Accordingly, the frequency from a self-operating diode laser may change. The slave laser which has a fixed frequency by the injection-locking method is subject to phase variation. The far-field pattern from a laser diode amplifier array is therefore affected by phase mismatching. Thus, the information on the phase variation due to the change in driving current of the laser diode array becomes very important for the quality of the far-field beam pattern.

## Correlation of Driving Current and Phase

The beam-combining methods are determined by the requirement of beam coherence or incoherence. For instance, wavelength division multiplexing (WDM) is an incoherent beam-combining method. On the other hand, ILA and TWA are regarded as coherent beam-combining methods (refs. 10 and 11). Accordingly, for fiber optic telecommunications which carry various multifrequency signals in a single fiber, WDM is necessary. To yield high-output beam power, coherent beam-combining methods are required.

When gain saturation is induced by the injected beam intensity (quenching effect), an output power which carries only the mode of the injected beam is generated (ref. 12). Thus, this output beam has the same phase and frequency as the injected beam. This principle can be effectively implemented for the generation of a single (coherent) high-power beam, as shown in figure 1. The beam from a master laser is split into several beams, and then each split beam is injected into the respectively aligned slave lasers.

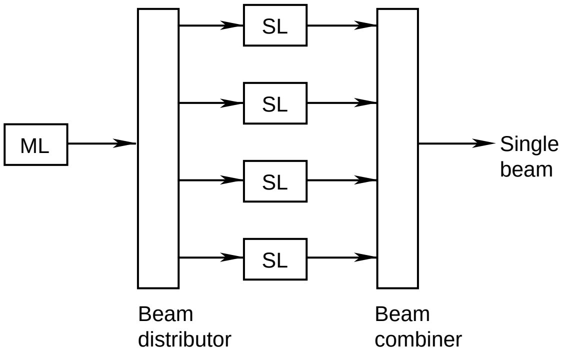


Figure 1. Arrangement of a master laser (ML) and slave lasers (SL) for beam combining.

The output beams from the injection-locked slave lasers are mutually coherent and facilitate beam combining by a binary grating or lens. The phase stability or matching is very important for beam combining and has direct influence on the beam-combining efficiency.

The variation of electron density in the semiconductor laser appears immediately as the variation of amplified frequency due to the changes in the refractive index and temperature of the gain medium (ref. 13). That is,

$$\Delta\nu = -\nu_o \left[A\delta N(I)/n + (\alpha_T + \beta_T)\delta T_1(I) + (\alpha_T + \beta_T)\delta T_2\right] \tag{1}$$

where $\delta N(I)$ is the variation of electron density by the driving current, $n$ the refractive index of the gain medium, $\nu_o$ the frequency of laser beam, $A$ a constant, $\delta T_1(I)$ the variation of temperature by current, $\delta T_2$ the variation of diode temperature due to ambient temperature changes, $\alpha_T$ the constant for the change in refractive index, and $\beta_T$ the constant for the change in cavity length.

Suppose that the surrounding temperature is stable. That is, $\delta T_2$ becomes zero. Then the main parameters for determining the coherence are directly related to the variations of electron density and temperature due to the fluctuation of driving current. F. Mogensen et al. (ref. 14) suggested that the injected phase $\phi$ between the master and slave lasers is determined by

$$\phi = -\arcsin\left(\frac{\Delta\nu}{\Delta\nu_L}\right) - \arcsin\alpha \tag{2}$$

where $\Delta\nu$ is the frequency difference between lasers, $\Delta\nu_L$ the injection-locking bandwidth, and $\alpha$ the linewidth enhancement factor (in the range from 3 to 10).

If $\Delta\nu$ is less than the injection-locking bandwidth of approximately 3 GHz, there will be only a relative change in phase from the injection-locked situation. Equation (2), for $\Delta\nu/\Delta\nu_L \ll 1$, becomes

$$\phi = -\frac{\Delta\nu}{\Delta\nu_L} - \arcsin\alpha \tag{3}$$

According to the experimental results, the frequency variation is proportional to the current variation. That is,

$$\Delta\nu = \gamma\Delta I \tag{4}$$

Substituting equation (4) into equation (3), the phase change with respect to the current variation is obtained as follows:

$$\Delta\phi = \frac{\gamma\Delta I}{\Delta\nu_L} \tag{5}$$

where $\gamma$ is a constant. In equation (5), the sign was omitted because the phase change is relative to the current. The correlation between the phase and the current can be established by experimental measurements. Once the correlation is obtained, then it may become a useful tool to control the phase mismatching among the slave lasers.

## Experimental Setup

### Frequency Stabilization

Frequency stabilization can be achieved either by the active feedback of electrical current corresponding to detected frequency variation or by the passive method of limiting the variations of temperature and current. Semiconductor lasers of the AlGaAs family usually have a single, translational mode of oscillation at room temperature when a stable temperature is maintained. Therefore, the experiment was carried out with the passive method. In the experiment, a thermoelectric (TE) cooler was used to control the temperature of the diode laser. The overall temperature fluctuation of the diode laser was limited to less than 0.02°C by laying the diode in a thermally controlled box. A temperature fluctuation of 0.02°C was estimated to cause a frequency drift of approximately 300 MHz. However, taking the injection-locking bandwidth of approximately 3 GHz into account, a temperature fluctuation of 0.02°C does not pose any significant problem to phase stability.

### Coherence Tests

The experimental setup for the measurement of beam coherence between the master and slave lasers is shown in figure 2. The output power of the lasers (Sharp Model LT015) used in the experiment was

30 mW at a wavelength of 830 nm. The beam from the master laser (ML), which was frequency stabilized by the temperature-controlled box, passes through a lens and the Faraday Isolator (FR). Then a portion of the beam is guided by beam splitter $BS_2$ and mirror $M_2$ into the spectrometer, which has a resolution of 0.5 Å. The rest of the beam after passing $BS_2$ is again split by $BS_1$. One portion of the split beam is directed to the slave laser (SL) and the other to mirror $M_1$. A portion of the output beam from the slave laser is guided into the spectrometer through $BS_1$ and $BS_2$. The charge-coupled device (CCD) camera simultaneously monitors the spectra from the master and slave lasers. The temperatures of both lasers are controlled by the respective TE coolers. Frequency variation of more than a few angstroms can be made by temperature control (using the TE cooler), and precision control of frequency variation can be made by the adjustment of the driving current. Consequently, when the beam frequency of the master laser matches with one of the slave laser oscillatory modes within the injection-locking bandwidth, the beam of the slave laser is injection-locked and mutually interfered with that of the master laser.

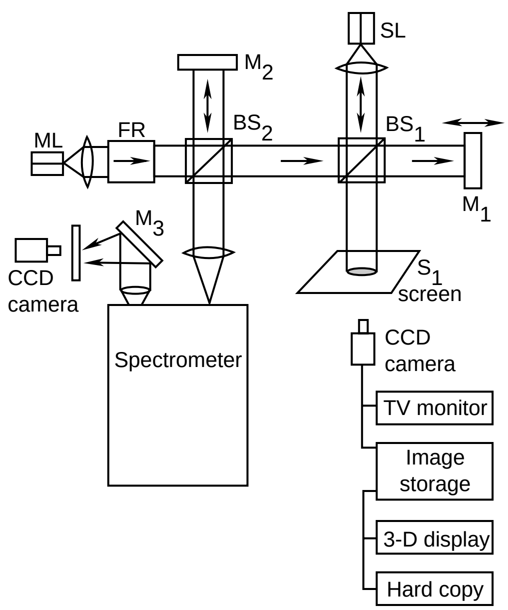


Figure 2. Twymann-Green interferometer for coherence measurement between the master and slave lasers. FR: faraday isolator; ML: master laser; SL: slave laser; $M_1$ and $M_2$: mirrors; BS: beam splitter.

The slave laser, $BS_1$, and $M_1$ form the Twymann-Green-type interferometer. The interference pattern between the beams of both lasers appears on screen $S_1$. This interference pattern was visually monitored by the densitometric CCD camera and the TV monitor, and stored by the image storage device. The brightness of the interference pattern was then measured by using the three-dimensional display and intensity measurement device. The intensity distribution of the interference pattern is Gaussian, as shown in figure 3. The brightness was obtained by the average of the minimum and maximum values.

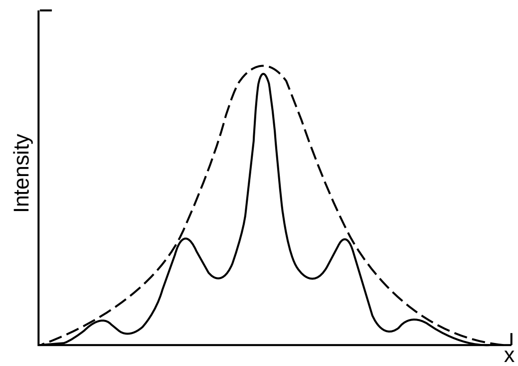


Figure 3. Gaussian intensity distribution of interference pattern. The abscissa signifies the distance across the interference pattern.

## Measurements of Phase Stability

Figure 4 shows the experimental setup for the measurements of phase change in the slave laser beam due to the variation of the driving current. The components $M_1$, $M_2$, $BS_1$, and $BS_3$ form the Mach-Zehnder-type interferometer. The phase of the master laser beam is fixed. Slightly increasing the driving current of the slave laser changes the phase of the slave laser beam. The interference pattern is then gradually displaced by the corresponding phase change of the slave laser beam. Let $\Delta x$ be the displacement from the original location of the interference pattern. Then the phase change is

$$\Delta\phi = \frac{\Delta x}{x} 2\pi \qquad (6)$$

where $x$ is the interval between the bright and dark images. The displacement $\Delta x$ was measured by using pictures of the interference pattern which were taken by the image-monitoring system and the thermal printer.

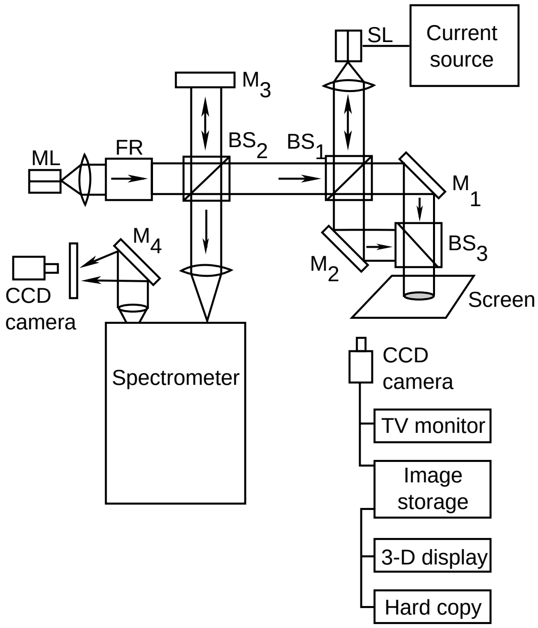


Figure 4. Mach-Zehnder interferometer for the measurement of phase change.

(a) Injection-locked spectra.

(b) Partially injection-locked spectra.

(c) Injection-locked interference pattern.

(d) Partially injection-locked interference pattern.

Figure 5. Injection-locking experiment images.

## Experimental Results

### Results of Coherence Tests

Figure 5(a) shows the spectrum when the two lasers are completely and mutually injection locked. The oval shape at the top in the picture shows the spectrum from the master laser; the bottom shape shows the spectrum from the slave laser. Figure 5(b) shows two translational modes of oscillation separated by approximately 3.5 Å when the slave laser is partially injection locked. Figure 5(c) shows the interference patterns when the master and slave lasers are completely and mutually injection locked, and figure 5(d) shows when they are partially injection locked. Figures 5(c) and (d) show the brightness of the interference pattern. The contrast of the completely and mutually injection-locked case (fig. 5(c)) is clearly greater than that of the partially injection-locked case (fig. 5(d)).

Figure 6 shows the changes in visibility when the optical path distance (OPD) between the SL–$BS_1$ interval and the ML–$BS_1$ interval was increased to the maximum, 1 m. The 1-m OPD is equivalent to approximately 300 MHz full width at half maximum (FWHM). In this regime, the variation of the brightness is almost negligible. The frequency bandwidth of the master and slave lasers is approximately 30 MHz as measured with a scanning Fabry-Perot spectrum analyzer with 30-MHz resolution. This value represents a coherence length of about 10 m.

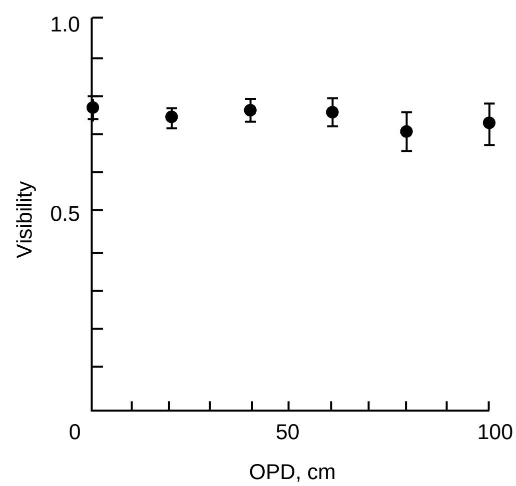


Figure 6. Beam visibility variation between the master and slave lasers with respect to OPD.

Figure 7 shows the visibility-variation measurements when the slave laser was replaced by a mirror for comparison. Figures 6 and 7 show that the characteristics of the master and slave laser beams are nearly the same. In other words, the coherence of the injection-locked slave laser beams is nearly the same as that of the master laser beams. Therefore, the injection-locking method does not degrade beam quality.

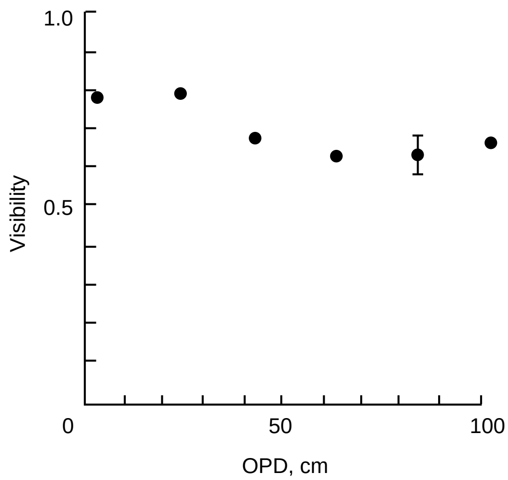


Figure 7. Visibility variation of the master beam with respect to OPD (slave laser replaced by a flat mirror).

### Measurement Results of Phase Stability

Figure 8 shows the measurement results of wavelength variation in the oscillator with respect to current fluctuation. The temperature was fixed at 14.4°C. As shown in figure 8, the wavelength gradually increases with increasing current and then shifts to another mode. The ratio of wavelength increment to current variation before the mode shift is approximately 0.15 Å/mA, which is equivalent to approximately 6.5 GHz/mA. That is, the constant $\gamma$ in equation (4) is 6.5 GHz/mA.

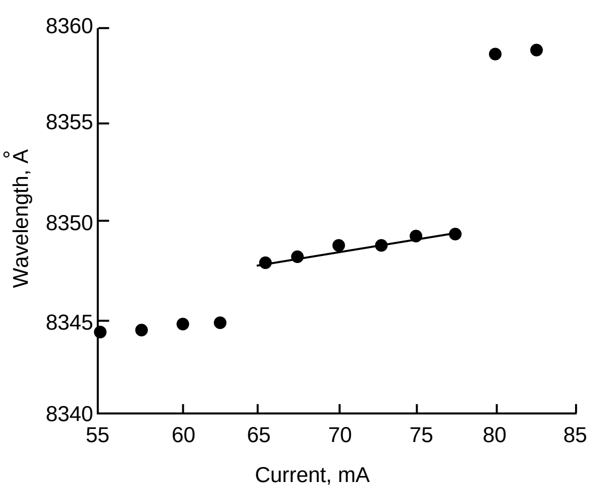


Figure 8. Wavelength variation of oscillator with respect to driving current change. Proportional constant is 0.15 Å/mA.

Figure 9 shows the measurements of phase change with respect to the driving current, using the setup as shown in figure 4. The current of the slave laser was varied in the vicinity of approximately 75 mA when the master laser was operated at the fixed current of 80 mA. The phase change is proportional to the driving current. The slope averages 2.5 radians/mA and resides between the maximum value, 3.0 radians/mA, and the minimum value, 2.0 radians/mA. Using equation (5), with 3 GHz for the bandwidth ($\Delta\nu_L$) of injection locking and 6.5 GHz/mA for $\gamma$, the theoretical slope becomes 2.2 radians/mA. This theoretical slope is not only within the error bound, but also confirms the results from the experiment. Combining the multilaser beams, the phase mismatch causes the beam-power variation at the central portion of the Airy disc of the far-field pattern. By this estimation, when the phase mismatch is 1.256 radians, the power loss rate becomes 10 percent (ref. 15), and the allowable current variation for the slave laser becomes approximately 0.5 mA.

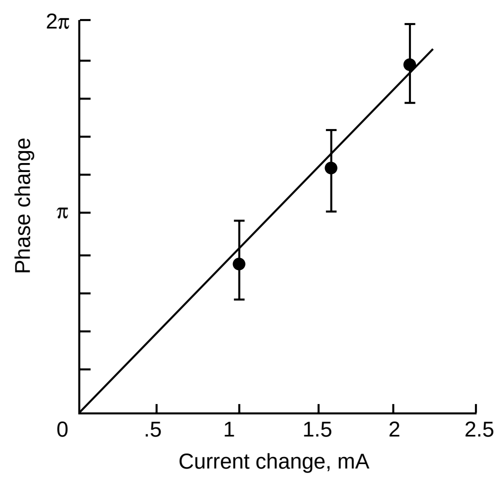


Figure 9. Phase changes of slave laser with respect to current variation as measured from experimental setup of figure 4. Proportional constant is 2.5 radians/mA.

## Conclusion

The coherence and phase change of the diode laser master oscillator and power amplifier system were measured by using Twymann-Green and Mach-Zehnder interferometers, respectively. The mutual spatial coherence between the injection-locked slave laser and the master laser was nearly identical to the master laser spatial self-coherence. The phase change with respect to current variation was about 2.5 radians/mA. Since the phase-matching tolerance for coherent beam combining is approximately $0.2\lambda$ (1.25 radians), the driving current need only be controlled within 0.5 mA. Present-day laser diode controllers are capable of controlling current to within

0.1 mA. Therefore, power supply current fluctuations will not limit high-power coherent beam combining performance.

NASA Langley Research Center
Hampton, VA 23665-5225
December 11, 1991

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