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High-Resolution Mode-Spacing Measurement of the Blue-Violet Diode Laser Using Interference of Felds Created with Time Delays Greater than the Coherence Time

So-Young BAEK, Osung KWON, and Yoon-Ho KIM*

Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Korea

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It is observed that the multi-mode cw blue-violet diode laser exhibits revival of interference when the interferometric path length difference is much greater than the coherence time of the laser and that the recurring interference peaks are separated by the same distance. We report that this unusual interference phenomenon can be used for high-resolution mode spacing measurement of the multi-mode cw blue-violet diode laser without using a high-resolution spectrometer.
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KEYWORDS: interference revival, blue-violet diode laser, mode spacing measurement

1. Introduction

Before the development of InGaN laser diodes,[1–4] access to blue or shorter wavelength laser lines was only possible by using mainframe gas lasers and/or harmonic generations of high-power pulsed lasers, such as, Q-switched Nd:YAG lasers, Ti:sapphire lasers, etc. Presently, blue, violet, or even ultraviolet (UV) semiconductor lasers with the average power of tens of milliwatt are available commercially. These blue-violet–UV diode lasers have strong potential applications (not to mention applications in high density optical data storage and printing) in quantum optics and quantum information research as compact pump sources (replacing mainframe UV lasers) for generating entangled photons via spontaneous parametric down-conversion.[5,6]

For many classical and quantum optical applications involving interferometry, it is important to have accurate knowlege of the spectral properties of the laser beam. Since high-power blue-violet–UV diode lasers available today tend to operate in the multi-mode (longitudinal modes) regime, the mode spacing measurement of the lasing spectra will tell us a lot about the spectral properties of the laser and, in addition, the laser diode itself. In fact, the mode spacing measurement of the blue-violet diode laser is important not only for characterizing the laser diode[1,2,7–9] but also for understanding the optical gain mechanism in InGaN laser diodes.[10,11]

Direct measurement of the mode spacing ($\Delta\lambda$) of the lasing spectra could be trivial if a spectrometer (or a monochromator) with sufficiently high resolution ($\sim 10^{-3}$ nm or better) were readily available.[1–3,7–9] This, however, is not the case for most researchers (e.g., in quantum optics or in classical interferometry) who make use of commercial blue-violet diode lasers since spectrometers (or monochromators) with the required resolution tend to be quite bulky and costly.

The other approach would be to indirectly determine $\Delta\lambda$ by making use of the relation derived from the resonant condition of the Fabry–Perot modes,[4,10]

$$\Delta\lambda = \lambda_0^2/2Ln_{\mathrm{eff}}, \tag{1.1}$$

where λ_0 is the wavelength of the peak of the lasing spectrum, L is the laser cavity length, and the effective refractive index, n_{eff}, of the waveguide at λ_0 is given as $n_{\mathrm{eff}} = n - \lambda_0\, dn/d\lambda_0$.[7–11] Quite naturally, if all the parameters on the right hand side of eq. (1.1) can be measured accurately, one can readily determine the mode spacing $\Delta\lambda$ of the diode laser.

The peak of the lasing spectrum λ_0 could be measured accurately by using a low cost spectrometer/monochromator or via interference. However, the information on the physical characteristics of the commercial diode laser, such as L and n_{eff}, is often proprietary and is generally not made available to the users. For the cavity length L, it is nevertheless possible to measure it if one risks the possibility of destroying the diode laser which can be rather costly.[12] Accurately measuring n_{eff} of the gain region of the laser diode, however, is not trivial and there are uncertainties regarding n_{eff} for the InGaN laser diode, causing so-called the mode spacing anomaly.[9–11,13,14] Therefore, indirect determination of the mode spacing $\Delta\lambda$ of the InGaN diode laser is still quite prohibitive as the measurement requires resources that are costly and not normally available to the users of such lasers.

In this paper, we first report on the observation of interference revival when the interfrometric path length difference is much greater than the coherence length of the multi-mode blue-violet cw diode laser. We then demonstrate that this unusual interference revival phenomenon can be used for low-cost high-resolution mode spacing measurement of the diode laser without resorting to a high-resolution spectrometer nor accurately measuring the physical characteristics of the laser diode. In addition, the interference revival effect reported in this paper should have quantum optics and quantum information applications in generating engineered entangled photon sources.

2. Interference Revival

Let us first briefly discuss the physics behind the revival of interference when the interferometric path length difference is much greater (by several orders of magnitude) than the coherence length. Consider the multi-mode cw field $E_{\mathrm{i}}(t)$ at any given point inside the diode laser cavity as the incoherent sum of multiple longitudinal modes,

$$E_{\mathrm{i}}(t) = \sum_m E_m \exp\{i[2\pi(\nu_0 + m\Delta\nu)t + \theta_m]\}, \tag{2.1}$$

where the subscript m is the mode number, E_m is the amplitude of a particular field mode, ν_0 is the frequency of the peak mode, $\Delta\nu$ is the frequency difference between the adjacent modes, and θ_m is the random phase of each longitudinal mode. Since the multi-mode field outside the

*E-mail address: yoonho@postech.ac.kr

laser cavity $E_o(t)$ is related to $E_i(t)$ with an attenuation factor due to the output coupler efficiency only, all temporal and spectral features of $E_i(t)$ are reflected on $E_o(t)$ without any change.

Consider now the instantaneous field amplitude outside the cavity. The individual field modes have random phases, so the multi-mode field $E_o(t)$ has a chaotic waveform.[15] However, the chaotic waveform should repeat itself at every time interval equal to $1/\Delta\nu$ because of the fact that the mode spacing (in the frequency domain) $\Delta\nu$ is constant. Since $1/\Delta\nu$ is equivalent to the time it takes for the cavity field to make one round trip inside the laser cavity of the length L and of the effective refractive index n_{eff}, the chaotic multi-mode cw field outside the cavity should repeat itself at every $T_p = 2L/v_g$, where $v_g = c/n_{\mathrm{eff}}$ is the group velocity of the light in the cavity. Then the round trip time T_p is calculated to be

$$T_p = 2Ln_{\mathrm{eff}}/c. \tag{2.2}$$

Therefore, by using eq. (1.1) and eq. (2.2), we arrive at the useful relation for determining the mode spacing,

$$\Delta\lambda = \lambda_0^2/cT_p = \lambda_0^2/L_p. \tag{2.3}$$

As mentioned earlier, λ_0 can be easily measured in a number of different ways. To determine the mode spacing accurately using eq. (2.3), one only needs to measure $L_p = cT_p$, the distance traveled by the chaotic out-of-the-cavity field $E_o(t)$ before it repeats itself.

Alternatively, we may use the frequency-domain analysis to obtain the mode-spacing $\Delta\lambda$. This way, we can arrive at the desired result, eq. (2.3), without using eq. (1.1) which is wavelength-dependent. As mentioned earlier, the frequency-domain mode spacing $\Delta\nu$ is constant. Since the chaotic field repeats itself at the time interval $1/\Delta\nu$, $\Delta\nu$ is directly related to the interference revival period T_p, which can be measured accurately, as $\Delta\nu = 1/T_p$. When desired, the frequency-domain mode spacing $\Delta\nu$ can be converted to $\Delta\lambda$ using the well-known relation, $\Delta\lambda = \Delta\nu\lambda_0^2/c$, thus arriving at eq. (2.3).

Experimentally, the measurement of L_p can be accomplished by observing interference of fields created at different times, in which the time delay is much greater than the coherence time of the laser, by using the unbalanced Michelson interferometer shown in Fig. 1. To analyze this phenomenon a bit more in detail, consider the multi-mode cw diode laser field $E_o(t)$ at the input to the interferometer shown in Fig. 1. The time averaged intensity I at the detector as a function of the path length delay τ is then calculated to be,

$$I \propto \langle |E_o(t) + E_o(t-\tau)|^2 \rangle \propto 1 + |g(\tau)| \cos(\omega_0\tau), \tag{2.4}$$

where the first order correlation function $g(\tau) = \langle E_o^*(t)E_o(t-\tau)\rangle / \langle E_o^*(t)E_o(t)\rangle$ and $\omega_0 = 2\pi c/\lambda_0$.

For $\tau \approx 0$, i.e., around the balanced position of the Michelson interferometer, eq. (2.4) predicts the typical Michelson fringes with a short coherence length l_c due to the multi-mode nature (large bandwidth) of the laser. When τ becomes bigger than the coherence time l_c/c, no interference occurs.

However, if the delay τ is further increased so that $\tau \gg l_c/c$ and becomes equal to T_p (the unbalanced Michelson interferometer), revival of interference should occur since the two superposed fields are now completely identical even

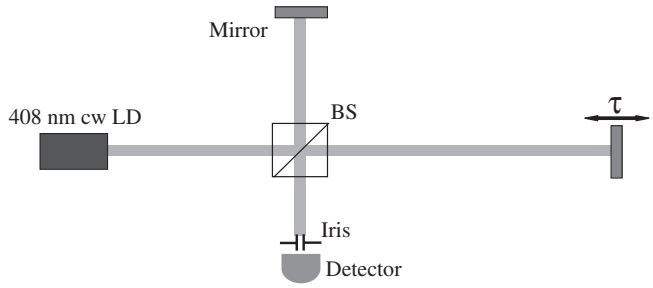

Fig. 1. Experimental setup. The path length difference between the two arms of the interferometer is much bigger (by several orders of magnitude) than the coherence length of the laser. BS is the 50/50 beamsplitter.

though they are born at different times. (Two-photon quantum interference can also be observed under similar conditions, see ref. 16.) Therefore, measurement of the path length difference of the interferometer at which the interference revival occurs is equivalent to measuring $L_p = cT_p$. Equation (2.3) can then be used to accurately determine the mode spacing of the multi-mode cw blue-violet diode laser.

3. Experiment

To demonstrate the revival of interference just described and its application in high-resolution mode spacing measurement, we setup an experiment using a commercial output-power-stabilized 408 nm diode laser (Coherent Cube) which is capable of delivering up to 50 mW of cw power (see Fig. 1). The experiment was performed at 40 mW output power setting and the diode temperature was set at 22°.

Before the interference experiment, we measured the lasing spectrum with a 1/2 m monochromator installed with a 1200 gr/mm grating blazed at 500 nm. The entrance and the exit slits were adjusted to 11 μm and the laser beam was focused at the slit with a 4 cm focus lens. The resolution of the monochromator, measured with a He–Ne laser, was approximately 0.06 nm. The spectral measurement is shown in Fig. 2. The peak emission wavelength was measured to be 408.20 nm with FWHM bandwidth of 0.50 nm. It is clear that our monochromator cannot resolve the mode spacing of the multi-mode blue-violet diode laser.

When the Michelson interferometer shown in Fig. 1 is scanned about the zero path length difference position, the usual Michelson fringe which is equivalent to the Fourier transform of the power spectrum of the light is observed (see Fig. 3). The full width at half maximum (FWHM) coherence length is measured to be 354.73 ± 3.94 μm and agrees well with the value obtained with the simple relation $l_c \approx \lambda_0^2/(\delta\lambda)_{\mathrm{BW}}$.

Next, the Michelson interferometer is scanned further so that the path length difference is much greater (by several orders of magnitude) than the coherence length l_c: interference disappears at this condition. We, however, observe the revival of interference when the path length difference is equal to integer multiples of L_p (see Fig. 4). As explained earlier, this is due to the fact that the chaotic multi-mode laser field $E_o(t)$ repeats itself at every T_p outside the cavity according to eq. (2.2). Smaller side peaks, which are sufficiently far away from the main peak, are due to unwanted reflections at various surfaces, including the beamsplitter. This happened because the some of the optics

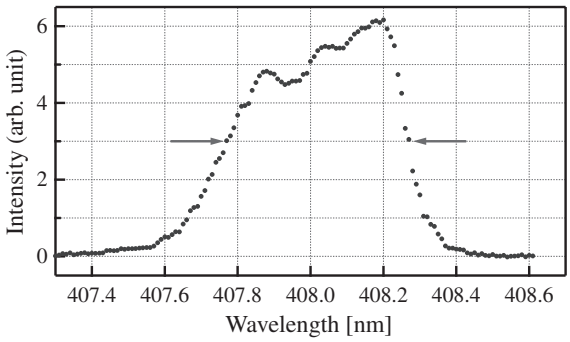

Fig. 2. The emission spectrum of the commercial blue-violet diode laser used in this experiment. The peak wavelength $\lambda_0 = 408.20$ nm and the FWHM spectral bandwidth $(\delta\lambda)_{BW}$ is approximately 0.5 nm.

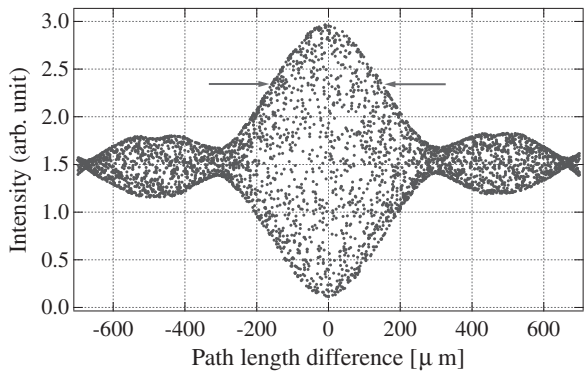

Fig. 3. The Michelson interferometer is scanned about the zero path length difference (balanced) position. The FWHM coherence length is 354.73 ± 3.94 μm.

used for the experiment were not properly coated at 408 nm. The visibility decrease is due to slight misalignment at large path length difference of the interferometer. The spacing, L_p, nevertheless remains the same. We note that the unwanted side peaks and the visibility decrease at large path length difference can be avoided by using proper optics and judicious alignment (see Fig. 5).

From the measured value of $L_p = 4.804 \pm 0.017$ mm, we are able to determine the mode-spacing of the multi-mode blue-violet cw diode laser. Since λ_0 is already known from Fig. 2, we readily determine that $\Delta\lambda = 0.0347$ nm for the laser (Coherent Cube) used in our experiment. Note that this value agrees well with a previous report on high-power blue-violet diode lasers reported in ref. 17. This suggests that the InGaN laser diode module used in our laser could in fact be a commercial product based on the proprietary InGaN design reported in ref. 17.

4. Discussion

Let us now briefly discuss the resolution of the mode spacing measurement. For a value θ which depends on two independently measured quantities x and y, the uncertainty $\delta\theta$ of the value $\theta(x, y)$ is given as,

$$\delta\theta = \sqrt{\left(\frac{\partial\theta}{\partial x}\delta x\right)^2 + \left(\frac{\partial\theta}{\partial y}\delta y\right)^2}, \tag{4.1}$$

where δx and δy are measurement uncertainties. Since the mode spacing $\Delta\lambda$ is determined by independently measuring λ_0 and L_p, the resolution is determined by measurement

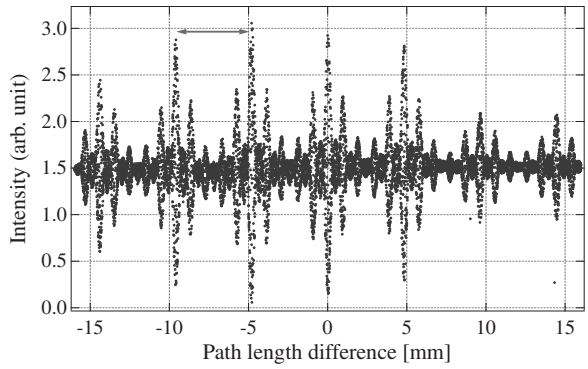

Fig. 4. Revival of interference is observed when the path length difference is equal to integer multiples of $L_p = 4.804 \pm 0.017$ mm. Smaller side peaks are due to unwanted surface reflections and the visibility decrease is due to slight misalignment at large path length difference of the interferometer. The spacing, L_p, however remains the same.

uncertainties related to λ_0 and L_p measurements. Using the measured values of λ_0 and L_p as well as eq. (2.3) and eq. (4.1), we roughly estimate that the uncertainty of the mode spacing can reach on the order of 10^{-4} nm. In fact, the calculated uncertainty of the mode spacing measurement reported in this experiment is 0.0001 nm. We therefore conclude that the commercial 408 nm cw diode laser (Coherent Cube at 40 mW) used in this experiment has the mode spacing $\Delta\lambda = 0.0347 \pm 0.0001$ nm. Note that, if the cavity length L were known, the effective refractive index n_{eff} of the gain region can be accurately determined with ease.

To further demonstrate the effectiveness of the mode-spacing measurement method described so far, the same test was performed on a different blue-violet diode laser system of the same model (Coherent Cube 405C). The diode temperature was set at 25° and the output power was maintained 30 mW. At this condition, the peak emission wavelength was measured to be 407.97 ± 0.07 nm with FWHM bandwidth of 0.51 nm (see Fig. 5). The balanced Michelson interferometer data show the coherence length of 355.81 ± 7.34 μm for the diode laser radiation, which is in good agreement with the FWHM bandwidth obtained from the spectral measurement.

When the path length difference is slightly increased so that the Michelson interferometer becomes unbalanced, the interference disappears. As expected, however, the periodic interference revival is observed as the path length difference is increased further (see Fig. 5). The period of interference revival is measured to be $L_p = 4.806 \pm 0.019$ mm. With these measurement data, we can readily determine the mode spacing of the blue-violet diode laser as $\Delta\lambda = 0.0346 \pm 0.0001$ nm. Note that, with improved optics and judicious alignment, unwanted side peaks observed in Fig. 4 have disappeared. In addition, the visibility of the recurring interference peaks remains almost the same even at very large path length difference (see Fig. 4 for comparison).

Finally, we note that a mode-locked Ti:sapphire laser is known to exhibit a similar interference revival effect. However, in this case, the effect is due to the fact that each ultrashort pulse is coherent (mode locked) to the adjacent pulse which is separated by the cavity round-trip time of the pulse. This effect has been used to demonstrate interesting two-photon quantum interference for ultrafast laser pumped

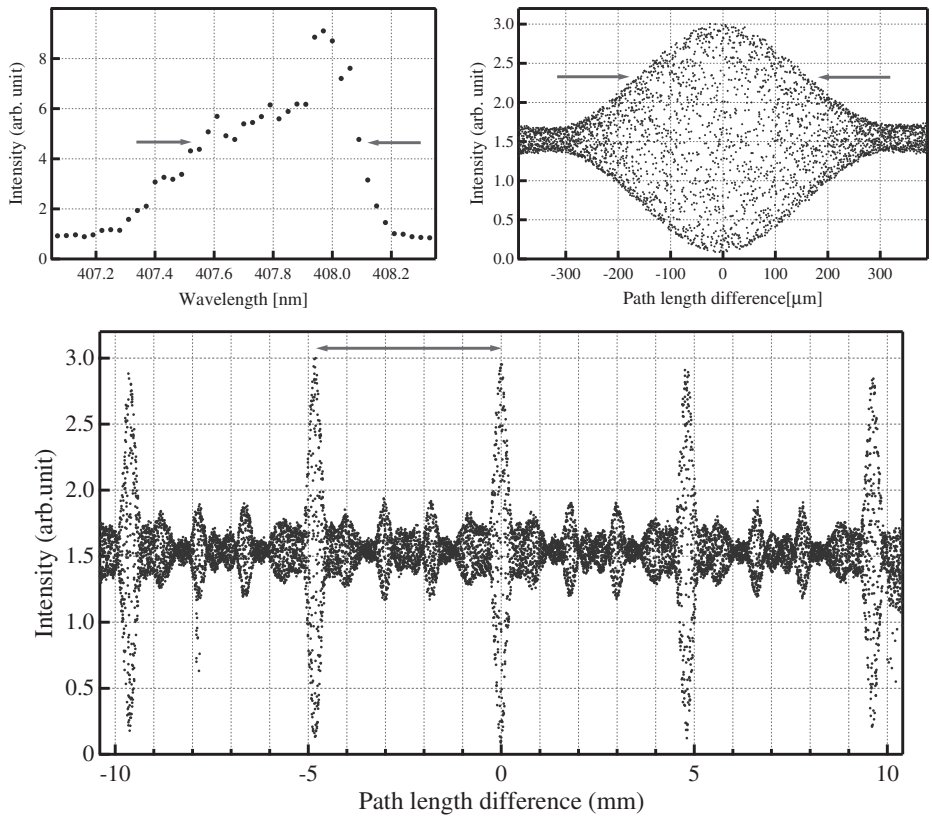

Fig. 5. Experimental data for a different diode laser of the same model (Coherent Cube). The peak emission wavelength was 407.97 nm with FWHM bandwidth of 0.51 nm. With improved alignment and optics, interference revival is clearly observed without strong side peaks and visibility degradation at large path length difference (see Fig. 4 for comparison).

spontaneous parametric down-conversion and shown to have quantum information applications.[18,19)]

The interference (coherence) revival of the chaotic multi-mode cw blue-violet diode laser reported in this paper can be exploited in a similar way. When a laser is used to pump the spontaneous parametric down-conversion process to generate entangled photon pairs, the coherence properties (spectral and temporal) of the pump laser are transferred to the two-photon entangled state.[16)] The coherence revival of the chaotic cw pump laser therefore will be completely transferred to the two-photon entangled state and a properly designed two-photon interference experiment will exhibit the same periodic interference revival effect but in this case the interference is of quantum origin, i.e., two-photon quantum interference. We therefore believe that the interference revival of a multi-mode cw diode laser reported in this paper can be exploited to demonstrate interesting new two-photon quantum interference and to generate engineered energy-time entangled photon states for multi-mode diode laser pumped spontaneous parametric down-conversion.

Acknowledgements

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