Characterising the Onset of Lasing Using Interferometric Photon Correlations

Xi Jie Yeo(1), Alvin Leow Zhen Wei(2), Lijiong Shen(1), Peng Kian Tan(1), Christian Kurtsiefer(1),(2)

(1) Centre for Quantum Technologies, National University of Singapore yeo.xi_jie@u.nus.edu
(2) Department of Physics, National University of Singapore

Abstract *We present a technique to characterize the onset of coherence in a semiconductor laser diode using interferometric photon correlation measurements, and we observe with increasing injection current a transition of light emitted by the diode from chaotic, to a chaotic-coherent light mixture, to coherent.*

Introduction

A key characteristic of a semiconductor laser diode is its threshold current. The laser diode emits laser light when operated above this current, and behaves as a light-emitting diode (LED) when operating below. A common method to determine the threshold current is to identify the injection current where the emitted optical power changes sharply[1]. However, this method cannot determine whether the light emitted has changed from being incoherent (LED) to coherent laser radiation, as the intensity measurement does not probe the nature of the light.

To do this, one can measure its second-order photon correlation $g^{(2)}$, where LEDs exhibit a "bunching" signature $g^{(2)}(0) > 1$ associated with chaotic light, while lasers exhibit $g^{(2)} = 1$[2],[3]. However, amplitude noise in the lasing regime[4],[5] may result in second-order photon correlation measurements exhibiting $g^{(2)}(0) > 1$, when $g^{(2)} = 1$ is expected. Thus, another method to investigate the transition of the nature of the emitted light is required to identify the onset of coherence.

We present such a method that is based on measuring interferometric photon correlations. In this technique, light from the laser diode is sent through an asymmetric Michelson interferometer and the timing correlations between the photo-events detected at the output ports are observed for different laser diode currents. Interferometric photon correlation measurements were initially used to study spectral diffusion in molecules[6],[7], and were also applied to differentiate between chaotic light and coherent light with amplitude fluctuations[8],[9]. Both types of light sources exhibit a "bunching" $g^{(2)}$ signature, and hence are indistinguishable by standard second-order photon correlation measurements. In contrast, interferometric photon correlation measurements reveal the fraction of coherent light in the chaotic-coherent mixture of light emitted by the laser diode as it transits from the LED regime to the lasing regime, allowing to more quantitatively characterise the onset of coherence.

Interferometric Photon Correlations

The light under test with an electric field profile $E(t)$ passes through an asymmetric Michelson interferometer with propagation delay Δ between the two arms, with electric fields

$$E_{A,B}(t) = \frac{E(t) \pm E(t+\Delta)}{\sqrt{2}} \tag{1}$$

at the output ports of the interferometer. The propagation delay Δ is chosen to be longer than the coherence time of the light. The correlation between these two ports is given by

$$\begin{aligned} &g^{(2X)}(t_2 - t_1) \\ =&\frac{\langle E_A^*(t_1)E_B^*(t_2)E_B(t_2)E_A(t_1)\rangle}{\langle E_A^*(t_1)E_A(t_1)\rangle\langle E_B^*(t_2)E_B(t_2)\rangle}. \end{aligned} \tag{2}$$

Using expressions in Eqn. 1, and the fact that dithering averages out some terms to 0, the correlation between the two ports expands to

$$\begin{aligned} &g^{(2X)}(t_2 - t_1) \\ \propto&\underbrace{\langle E^*(t_1)E^*(t_2)E(t_2)E(t_1)\rangle/4 + \langle E^*(t_1+\Delta)E^*(t_2+\Delta)E(t_2+\Delta)E(t_1+\Delta)\rangle/4}_{\text{conventional } g^{(2)} \text{ terms}} \\ &\underbrace{+ \langle E^*(t_1+\Delta)E^*(t_2)E(t_2)E(t_1+\Delta)\rangle/4 + \langle E^*(t_1)E^*(t_2+\Delta)E(t_2+\Delta)E(t_1)\rangle/4}_{\text{time-shifted } g^{(2)} \text{ terms}} \\ &\underbrace{- \langle E^*(t_1+\Delta)E^*(t_2)E(t_2+\Delta)E(t_1)\rangle/4 - \langle E^*(t_1)E^*(t_2+\Delta)E(t_2)E(t_1+\Delta)\rangle/4}_{g_{\text{int}}^{(2X)} \text{ terms}}. \end{aligned} \tag{3}$$

Type of Light	$E(t)$	$g^{(2)}(\tau=t_2-t_1)$	$g^{(2X)}_{\text{int}}(\tau=t_2-t_1)$
Chaotic	$E_0\frac{e^{i\omega t}}{\sqrt{N}}\sum_j^N e^{i\phi_j(t)}$	$1+e^{-2\|\tau\|/\tau_c}$	$-e^{-2\Delta/\tau_c}-e^{-2\|\tau\|/\tau_c}$
Coherent	$E_0e^{i\omega t}e^{i\phi_j(t)}$	1	$-e^{-2m/\tau_\phi}$

Tab. 1: Expressions of $g^{(2)}$ and $g^{(2X)}_{\text{int}}$ for chaotic and coherent light. Here, N is the number of independent emitters of coherent light in the chaotic source, τ_c is the coherence time of the chaotic source, τ_ϕ is the coherence time of the coherent light and $m=\min(\Delta,\|\tau\|)$.

The first $g^{(2)}$ terms in Eqn. 3 have the form of conventional second-order photon correlation functions, whereas the second group of terms are simply versions of $g^{(2)}$ that are time-shifted in their argument by a time Δ and $-\Delta$, respectively. The terms grouped as $g^{(2X)}_{\text{int}}$ occur as a result of light interfering at the output ports.

The expressions for $g^{(2)}$ and $g^{(2X)}_{\text{int}}$ for coherent and chaotic light are shown in Tab. 1, using the models of electric fields for coherent and chaotic light found in Ref.[10].

The expected correlations of $g^{(2)}$, $g^{(2X)}_{\text{int}}$ and $g^{(2X)}$ for coherent and chaotic light are shown in Fig. 1. We also show the expected correlations of a light source with 50:50 mixture of coherent and chaotic light, obtained by an equally weighted sum of $g^{(2)}$ and $g^{(2X)}$ for coherent and chaotic light as predicted in Ref.[8].

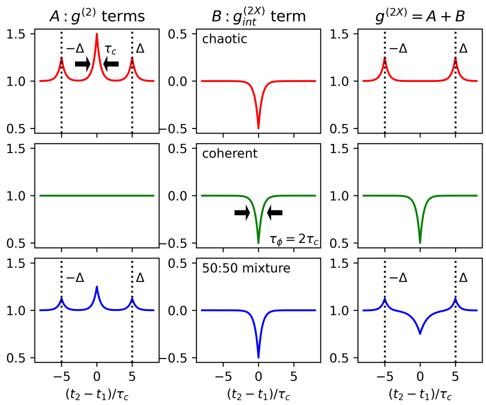

Fig. 1: Expected correlations of $g^{(2)}$, $g^{(2X)}_{\text{int}}$ and $g^{(2X)}$ for chaotic light (red), coherent light (green) and 50:50 chaotic-coherent light mixture (blue), where τ_c is the coherence time of the chaotic light, $\tau_\phi=2\tau_c$ is the coherence time of the coherent light, and $\Delta=5\tau_c$ is the propagation delay between the interferometric arms.

Interferometric Photon Correlations near the Lasing Threshold

The observed optical power emitted by a laser diode (Photodigm PH760DBR) is shown in Fig. 3(a) as a function of the injection current, where a sharp change in intensity is observed around 52.80 mA. We now measure $g^{(2X)}$ near this transition current.

To measure $g^{(2X)}$, we spectrally filter the light emitted by the laser diodeusing a grating monochromator and an etalon, with an effective spectral filter bandwidth of approximately 6 GHz. The spectrally filtered light is sent through an asymmetric Mach-Zehnder interferometer with a 50 ns propagation delay between the two paths of the interferometer. This is accomplished with a 10 m long single mode optical fibre (Fig. 2). Photoevents at each output port of the interferometer are detected by single photon avalanche detectors and time-stamped. The correlations are then extracted numerically by histogramming the time differences of all pairs of the timestamped events. The histogram is correctly normalised by multiplying the total measurement time and dividing by the product between the number of events at each channel and the size of the timing bins. Sample measurements showing signatures of coherent, mixture and chaotic light are shown in Fig. 3(b)-(d).

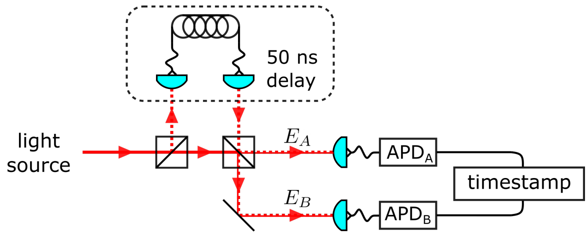

Fig. 2: Experimental setup for measuring interferometric photon correlations. The spectrally filtered light from the laser diode is split at a non-polarising beam splitter and coupled into a delay fibre before recombining at another non-polarising beam splitter. APD: Avalanche single photon detectors.

Extracting percentage of coherent light in mixture

The measurements of $g^{(2X)}$ were fitted with the weighted sum of $g^{(2X)}$ expressions for chaotic and coherent light as shown in Tab. 1. The value of $g^{(2X)}(0)$ ranges from 0.5 (for coherent light) to 1 (for chaotic light). We extract the fraction of coherent light in the mixture from the expression

$$\frac{1-g^{(2X)}(0)}{0.5}. \tag{4}$$

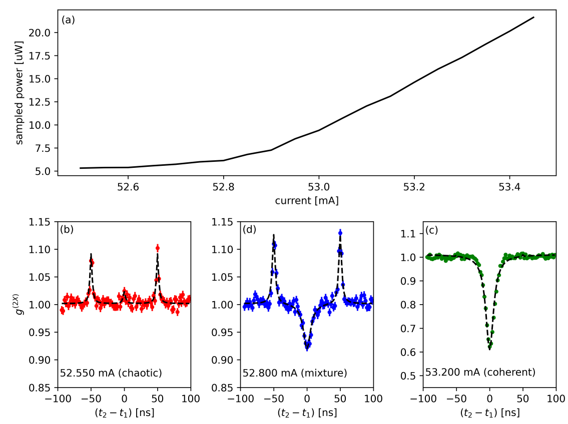

Fig. 3: (a) sampled power emitted by the laser diode as a function of injection current. (b)-(d) $g^{(2X)}$ measurements showing signatures of chaotic light at 52.55 mA (red), mixture at 52.80 mA (blue) and coherent light at 53.20 mA (green).

The extracted fraction of coherent light for different injection currents is shown in Fig. 4. It was found to increase with the injection current, and saturates at 0.8, not reaching the expected value of 1 even at the largest current (53.4 mA) where the laser was clearly operating above threshold. We attribute this observation to the limited visibility of the interferometer, which results in $g^{(2X)}(0) > 0.5$ even for coherent light, leading to a smaller fraction of coherent light by simply using Eqn. 4. The extracted fraction of coherent light takes even an unphysical negative value at 52.50 mA and 52.55 mA due to a small peak appearing at $g^{(2X)}(0)$, which we again attribute to the limited visibility of the interferometer. Increasing the visibility of the interferometer should hopefully resolve this issue.

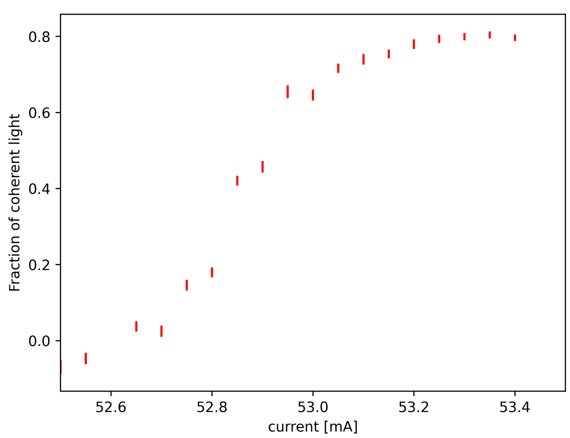

Fig. 4: Fraction of coherent light as a function of injection current extracted from the fit of $g^{(2X)}$ measurements.

Conclusion

We presented a method to extract the fraction of coherent light emitted by a laser diode at different injection currents from interferometric photon correlation measurements. The fraction of coherent light was found to increase with injection current, which agrees with the expectation that the light emitted by the laser diode changes from an incoherent LED to coherent laser radiation.

References

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