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Dependence of an LED Noise on Current Source Impedance

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Photocurrent noise from an LED is measured as a function of the current source impedance. Bandwidth of noise reduction is found to be equal to the inverse of the time constant which is the product of the differential resistance of the LED and a paralelly connected capacitance. The experimental results are described in terms of a simple equivalent circuit.

KEYWORDS: squeezed light, LED, noise, constant current, impedance

§1. Introduction

It is known that squeezed light is emitted from laser diodes (LD) or light-emitting diodes (LED) driven by constant-current power supply.[1-3] The mechanism of squeezing of light from an LD or an LED is described by A.Shimizu et al.,[4] where they have pointed out that dissipation process in the current-limitting resistor plays an important role in the squeezing process. However, Imamoğlu et al. have pointed out that the injection current regulation is not sufficient but a macroscopic Coulomb blockade effect within the diode junction is necessary for the squeezing.[5] Very recently Kim et al. have demonstrated this effect by using home-made diodes with various junction capacitances.[6] Abe et al. have observed similar phenomena by using a high-speed diode.[7]

In this paper we report an experiment by using an LED with various external capacitors connected paralelly to the LED and demonstrate that the external capacitance plays the same role in the macroscopic Coulomb blockade effect as the internal junction capacitance. Therefore it is possible to consider an equivalent circuit which explains phenomenologically the squeezing process in an LED without describing microscopic processes in the LED.

The external capacitance is regarded as a low impedance current source, i.e. as a constant-voltage source for the LED rather than as a part of the junction capacitance of the LED. It is known

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that constant-current(CC) driving reduces light noise below the shot-noise level but constant-voltage(CV) driving gives the standard shot noise. Whether the driving condition is CC or CV depends on the impedance of the power supply. We measured noise spectra in the intermediate region between CC and CV in order to obtain the condition for squeezing. It is found that the noise spectra can be described in terms of a simple equivalent circuit.

§2. Experiment

Figure 1 shows the schematical circuit diagram for the experiment. Light from a high-efficiency light-emitting diode LED (Hamamatsu photonics L2656) is received by a PIN photodiode PD (Hamamatsu photonics S3590). The responce time of LED is 2.5μs and the cut-off frequency of PD is 45MHz. A resistor R (2kΩ) larger than the differential resistance (41.7Ω) of LED is used as a current limiter. In order to change the impedance of the current source we connected various capacitors to LED. The driving current I_{LED} is 1.0mA and the photocurrent I_{PD} is 0.083mA. The total current conversion efficiency $\eta = I_{PD}/I_{LED}$ is 0.083. We measured the dependence of I_{PD} on I_{LED} and obtained the differential efficiency $\eta_d = 0.11$ where η_d is defined as dI_{PD}/dI_{LED}.

Figure 2 shows the circuit used in the experiment. The variable capacitor C in Fig. 1 is replaced by two capacitors, C_1 (capacitance C_1) and C_2 (capacitance C_2) and a diode switch SW. When diode switch SW is closed by current injection into SW, the capacitance C of the current source is $C_1 + C_2$. When SW is open, C_2 is disconected and $C = C_1$. We used a large capacitance (11μF) as C_2 and relatively small capacitance (from 0 to 10μF) as C_1. When the switch is closed, LED is driven under CV (constant-voltage) condition owing to the large capacitance and the photocurrent has a shot noise. When the switch is open, LED is driven under an intermediate condition between CV and CC and the photocurrent noise is expected to be reduced below the shot-noise level corresponding to the value of C_1.

The photocurrent signals were digitized by a storage oscilloscope and transferred to a computer. The diode switch is controlled through GP-IB bus by the computer. We measured the photocurrent noise with SW opened and that with SW closed (under CV condition) alternatively. Measurements were repeated 4000 times.

Figure 3 shows noise spectra for $C_1 = 0.01\mu F$ as functions of frequency f. The upper trace shows the standard shot noise intensity under CV condition. The lower trace shows the noise intensity for $C = 0.01\mu F$, which is reduced at low frequencies.

The ratio of the two noise spectra, i.e. Fano factor $F(f)$, is shown in Fig. 4. The line represents the fitted curve as will be described in the next section. The Fano factor $F(f)$ is reduced below unity for low frequencies and approaches unity as f increases.

§3. Model

We consider an equivalent ac circuit shown in Fig. 5 in order to explain the experimental results. The LED noise is assumed to come from driving current fluctuations. An equivalent noise V_n is applied to resistor r of the LED through the current-limitting resistor R and a bypass capacitor C. A voltage noise v_n is superposed on the driving dc voltage. This noise comes from the voltage fluctuation V_n of the LED and is given by:

$$v_n = V_n \frac{r}{Z + r}, \tag{3.1}$$

where Z is the impedance of the parallel circuit of R and C. This impedance is given by the following equation:

$$Z^{-1} = R^{-1} + i2\pi f C. \tag{3.2}$$

The ratio of the noise powers of the source and the LED is given by:

$$F_1 = |v_n/V_n|^2, \tag{3.3}$$

and can be rewritten as follows.

$$F_1 = 1 - \frac{1}{1 + (2\pi f r C)^2}, \tag{3.4}$$

where $R \gg r$ is assumed.

In the actual experiment only a small part of the emitted light is converted to the photocurrent. Therefore we rewrite the Fano factor in terms of $\eta (< 1)$ as follows:

$$F(f) = 1 - \eta(1 - F_1) = 1 - \eta \frac{\tau^{-2}}{f^2 + \tau^{-2}}, \tag{3.5}$$

where

$$\tau = 2\pi r C. \tag{3.6}$$

This equation gives the squeezing bandwidth equivalent to that given by the macroscopic Coulomb blockade model if the differential resistance r of the LED is replaced by $r = k_B T/eI$.6) This relation is derived from the current-voltage characteristic of the diode except for a numerical factor. We carried out the least squares fitting with the fitting parameters η and τ. An example of the fitted curves is shown in Fig. 4. The time constant τ obtained from the fitting for various capacitances are shown in Fig. 6. We carried out the least squares fitting of a straight line to the dependence of τ on C assuming the following relation:

$$\tau = 2\pi r C + \tau_0. \tag{3.7}$$

We obtained $\tau_0 = 2.59\,\mu s$ and $r = 34.7\,\Omega$. The obtained resistance (34.7 Ω) is smaller than but comparable to the measured differential resistance (41.7 Ω). The time constant (2.59 μs) obtained from the fitting is not so short as expected from the photodetector response time ($2.5\mu s$). An extra (effective) capacitance of the photodetector is expected to be responsible for the difference but it has not yet been identified.

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Figure Captions

Fig. 1

Experimental circuit for measurement of noise of an LED driven by a constant current limited by resistor R.

Fig. 2

Switching of capacitance by using diode switch SW. When SW is turned on, C_2 is added to C_1.

Fig. 3

Noise spectra of the LED for low impedance driving (upper trace) and for higher impedance driving (lower trace).

Fig. 4

Noise power reduction ratio, i.e. Fano factor F for $C = 0.01\mu F$ is measured (closed circles) as a function of noise frequency. A theoretical curve is fitted to the experimental results and the noise reduction bandwidth is obtained.

Fig. 5

An equivalent circuit is assumed in order to describe the dependence of ac noise in the LED (r) on capacitance C.

Fig. 6

Time constant τ derived from the Fano factor curve is calculated and theoretical line $\tau = 2\pi rC + \tau_0$ is fitted.