A new semiclassical model to analyze sub-Poissonian light in high-impedance-driven semiconductor light emitters

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Abstract

We propose a new and simple semiclassical model to analyze sub-Poissonian light in high-impedance, constant-current-driven semiconductor light emitters, and obtain some new and interesting results. Our study shows that the model gives a simple and distinct physical picture to explain the suppression mechanism of intensity noise in high-impedance-driven semiconductor light emitters. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Sub-Poissonian light (i.e., amplitude-squeezed light) are of great fundamental and practical interest, which can be widely applied in precision measurements [1], optical communication [2], quantum optical tap (or repeater) [3,4] and generation of non-classical array light [5–7], laser Doppler anemometry [8], and so on.

There are four main methods to generate sub-Poissonian light [9], but high-impedance, constant-current (HICC) driven semiconductor light emitters, including light-emitting diodes (LED) and laser diodes (LD), is the simplest and most successful one, which was first proposed and demonstrated by Yamamoto’s group [10,11], and has been widely studied, both theoretically [10,12–17] and experimentally [11,18–22]. Nearly all of experimental results [11,18–22] can be explained well by the corresponding quantum theory [10,12–14], or semiclassical theory [15,16], even classical theory [17]. However, the treatments for quantum-noise squeeze and correlation mechanisms in quantum theory are rather complicated and overelaborate (tedious), whereas the physical picture for the description of quantum-noise correlation and suppression in semiclassical or classical theory are not too clear and not audio-visual, and no any theory to date has given a simple and analytical expression to directly describe the relationship between the Fano factor $F$, or the squeezing $S$ of amplitude noise and the series-coupled source resistance $R$ (i.e., self-
feedback resistance) in a LED (or LD). The internal electronic negative-feedback mechanism for amplitude noise compression in HICC-driven LED (or LD) was mentioned by Yamamoto et al. [10] and Edwards and Pollard [16], but they did not give the corresponding quantum or semiclassical model and its treatment method.

Recently, Masalov et al. proposed a concept of an anticorrelation light state to explain the suppression mechanism in an in-loop photocurrent noise [23]. In this Letter, we will propose a simple semiclassical model and give a new treatment method to analyze open-loop sub-Poissonian light in a HICC-driven LED (or LD). The treatment method in this model is not only simple and convenient, but the physical picture is also very clear and intuitive. In Section 2, we present a new semiclassical model and equivalent circuit to describe the suppression of driven-current noise in a HICC-driven LED (or LD). In Section 3, by using our new model, the output intensity fluctuations from the LED (or LD) are derived and analyzed. In Section 4, the photocurrent fluctuations from the detected LED (or LD) output light are derived and discussed, and we present some calculation examples and compare our results with ones from other models, and then outline our semiclassical model in Section 5. We summarize the main results and conclusions in the last section.

2. Semiclassical model

2.1. Semiclassical model and equivalent circuit

First, let us simply review the principle to generate an amplitude-squeezed light in pump-noise suppressed semiconductor devices. A scheme of amplitude-noise suppression in a HICC-driven LED (or LD) is shown in Fig. 1, where $U$ and $R$ are a low-noise constant-current source and a series-coupled source resistor, respectively, and they form a high-impedance bias circuit of the LED (or LD). The pump-current noise of the LED (or LD) can be suppressed to be below its shot-noise level (SNL) by a HICC source, and this quite pump-electron stream (sub-Poissonian current, or sub-shot-noise electronic current) can be converted into a quite photon stream (sub-Poissonian light) by a high-efficiency LED (or LD) [11,16,18–22], or converted into a sub-Poissonian photocurrent by a high-efficiency photon-emitting and detecting system composed of a LED (or LD) and a PD [3–7], the corresponding
Fano factor is given by [16,18]

\[
F \equiv \frac{\langle \Delta I^2 \rangle}{\langle \Delta I^2_{SNL} \rangle} = 1 - \eta,
\]

where \( \eta \) is the light-emitted quantum efficiency of LED or LD, or total current converted efficiency, \( I \) represents the corresponding light intensity (or photocurrent).

Next, we will introduce our new semiclassical model to analyze amplitude squeezed light in a HICC-driven LD (or LED), and derive a series of simple and analytical equations to describe the driven-current fluctuations, sub-Poissonian light and sub-shot noise photocurrent. In fact, as Yamamoto and Edwards pointed out [10,16] that a high-impedance constant-current (HICC) source allows the voltage across the diode (LED or LD) to fluctuate, the carrier number are self-stabilized by an internal electronic-negative-feedback effect from the photon-emission process. So a sub-Poissonian-driven current can be regarded as a result of a self-stabilized sub-Poissonian photon-emission process by a feedback resistor \( R \).

From this idea, our simplified model for a HICC-driven LED or LD (see Fig. 1) can be depicted with Fig. 3. It can be seen from Fig. 3 that except for a conventional function of LED (or LD) to emit photons, another new function of photon emitters corresponds to an electron-current modulator (ECM), its driven-current fluctuations can be regarded as to be composed of two noise components when the modulation depth of the ECM is very small: one is a quantum noise component \( \delta i_N \) from an inherent Poissonian driven-current noise in the LD (or LED) when \( R = 0 \), another component is a classical modulated-noise one \( \delta i_M \) from the feedback signal of the source resistance \( R \). So when the negative feedback effect from the resistance \( R \) makes the classical variations opposite to the quantum Poissonian fluctuations (i.e., when there is an anticorrelation effect between two noise components), the total driven-current noise will be controlled and compressed below its SNL by a negative current-feedback signal from the resistor \( R \).

\[ -G (\delta i_M + \delta i_N). \]

Here the resistor \( R \) corresponds to a negative self-feedback amplifier with a gain \( G = R/R_d \), \( R_d \) is the diode’s differential resistor, which is about 1–20 \( \Omega \) and inversely proportional to the driven current \( i = \langle i \rangle + \delta i \). Recently, both theoretical and experimental studies show that when \( R \gg R_d \) (i.e., \( G \gg 1 \)), the pump-current fluctuations will be suppressed below the SNL; while \( R < R_d \), or \( R = 0 \) (that is, there is no negative feedback effect in the driven current), the fluctuations of pump current are nearly or equal to the SNL [10–22]. This shows that an anticorrelation effect between the classical modulated-noise component and the quantum Poissonian-noise one in the pump current fluctuations should be existed.

In Fig. 3, \( \delta i_M \) and \( \delta i_N \) are the classical modulated-noise component and quantum Poissonian-noise one in the driven-current fluctuations \( \delta i \), respectively, \( \delta i_{PM} \) and \( \delta i_{PN} \) are the classical modulated-noise component and quantum Poissonian-noise one in the detected-photocurrent fluctuations \( \delta i_P \); whereas \( \delta I_M \) and \( \delta I_N \) are the classical modulated-noise component and quantum Poissonian-noise one in the intensity fluctuations \( \delta I \), and \( \langle i \rangle \), \( \langle I \rangle \) and \( \langle i_P \rangle \) are the corresponding mean driven-current, intensity and photocurrent, respectively.

2.2. Suppression of driven-current noise

From our semiclassical model as shown in Fig. 3, the negative feedback action of the driven-current noise from the series-coupled source resistance \( R \) will result in an anticorrelation effect between the quantum Poissonian-noise component \( \delta i_N \) and the classical modulated-noise one \( \delta i_M \), and then the pump-current noise can be reduced to be arbitrarily-small level below its SNL by increasing the feedback gain \( G \) (that is, increasing the source resistance \( R \)), which is similar...
to the case in the suppression of in-loop photocurrent fluctuations [23,24].

Now we will prove theoretically that there is indeed an anticorrelation effect between two noise components in the driven-current fluctuations, and show that this anticorrelation effect is generated by the negative feedback action of pump-current noise from the source resistance $R$. Assuming the driven-current noise $\delta i$ is far larger than the Johnson–Nyquist thermal noise and shows the shot noise property, $\langle \delta i^2 \rangle = (i)$ (that is, the Poissonian distribution) when $R = 0$, the total pump-current noise is given by

$$\delta i = \delta i_M + \delta i_N. \quad (2)$$

which will be amplified by the equivalent feedback amplifier ($R$) with a gain $-G$, and converted into the classical modulated-noise component $\delta i_M$ by the negative feedback-controlled ECM, and then we have

$$-G(\delta i_M + \delta i_N) = \delta i_M, \quad (3)$$

or the relationship between the $\delta i_N$ and $\delta i_M$ is given by

$$\delta i_M = - \frac{G}{1+G} \delta i_N. \quad (4)$$

Similar to the definitions in Ref. [24], the first-order correlation function $g^{(i)}_{MN}$ between two noise components ($\delta i_M$ and $\delta i_N$) in the driven-current fluctuations and its normalized correlation coefficient $C^{(i)}_{MN}$ are derived, respectively, as

$$g^{(i)}_{MN} \equiv \langle \delta i_M \delta i_N \rangle = - \frac{G}{1+G} \langle \delta i^2_N \rangle$$

$$= - \frac{G}{1+G} \langle i \rangle, \quad (5)$$

and

$$C^{(i)}_{MN} \equiv \frac{\langle \delta i_M \delta i_N \rangle}{[\langle \delta i^2_M \rangle \langle \delta i^2_N \rangle]^{1/2}} = -1. \quad (6)$$

Eq. (5) shows that there is a strong anticorrelation effect between the quantum Poissonian-noise component $\delta i_N$ and the classical modulated-noise one $\delta i_M$ in the pump-current fluctuations, and its anticorrelation strength depends on the feedback gain $G$ (i.e., the feedback resistance $R$) only. Whereas Eq. (6) further indicates that this anticorrelation effect can be complete (100%) under the ideal condition (that is, without considering the influence of the Johnson–Nyquist thermal noise from the resistor $R$). This shows that this anticorrelation effect indeed results from the negative self-feedback action of the source resistance $R$ for the pump-current fluctuations. Therefore, the pump-current fluctuations in the HICC-driven LD (or LED) can be reduced to an arbitrarily-small level below its SNL.

Using Eqs. (2) and (3), the total pump-current noise in the HICC-driven LD (or LED) is given by

$$\langle \delta i^2 \rangle \equiv \langle (\delta i_M + \delta i_N)^2 \rangle = \frac{1}{(1+G)^2} \langle \delta i^2_N \rangle$$

$$= \frac{1}{(1+G)^2} \langle i \rangle, \quad (7)$$

and the corresponding Fano factor is

$$F^{(i)} \equiv \frac{\langle \delta i^2 \rangle}{\langle \delta i^2_{SNL} \rangle} = \frac{1}{(1+G)^2}. \quad (8)$$

From Eqs. (7) and (8), when $R = 0$ (that is, $G = 0$), we obtain $\langle \delta i^2 \rangle = \langle i \rangle$ and $F^{(i)} = 1$; while $G$ is large enough (that is, $G \gg 1$), we have $\langle \delta i^2 \rangle \approx 0$, and $F^{(i)} \approx 0$. This shows that if there is not the feedback resistor $R$ in the constant-current-driven LED (or LD) circuit, the pump-current fluctuations are at the SNL; while there is the resistor $R$, the driven-current noise will be reduced below its SNL. Particularly, when $R$ is large enough compared with the diode’s differential resistor $R_d$ (that is, $R \gg R_d$), the driven-current noise will be reduced to be an arbitrarily-small level below its SNL, which is consistent with other results from quantum theory [10,12] and semiclassical theory [16].

3. Sub-Poissonian light

Setting the averaged intensity of the LED (or LD) output light is $\langle I \rangle$, the corresponding classical modulated-noise component and quantum Poissonian-noise one in the output intensity fluctuations are $\delta I_M$ and $\delta I_N$, respectively, and the photon emitting efficiency of the LED (or LD) is $\eta_E = \langle I \rangle/\langle i \rangle$, then we have

$$\langle I \rangle = \eta_E \langle i \rangle, \quad (9)$$

$$\delta I_M = \eta_E \delta i_M, \quad (10)$$

and

$$\langle \delta I^2_M \rangle = \left( \frac{G}{1+G} \right)^2 \eta_E^2 \langle I \rangle. \quad (11)$$
\[ C(I) = \frac{\eta_E^2 \delta I_N^2 + \eta_E(1 - \eta_E)\langle I \rangle}{(1 + \eta_E)^2} \]  

Eq. (10) shows that the classical modulated-noise component \( \delta I_M \) in the output intensity fluctuations of the LED (or LD) is only from the classical modulated-noise one \( \delta I_N \) in the driven-current fluctuations; whereas Eq. (12) indicates that the quantum intensity-noise component \( \delta I_N \) contains two independent noise sources: an inherent quantum Poissonian noise (the first item in Eq. (12)) from the quantum Poissonian pump-current noise \( \delta I_N \) and an incompletely-photon-emitting induced quantum noise (the second item in Eq. (12)) due to the non-unity quantum emitting efficiency of the LED or LD \((\eta_E < 1)\). Similarly, the correlation function \( \langle \delta I_M \delta I_N \rangle \) between the quantum Poissonian-noise component \( \delta I_N \) and the classical modulated-noise one \( \delta I_M \) in the output intensity fluctuations of the LED (or LD) is given by
\[
\delta_{MN}^{(I)} = \langle \delta I_M \delta I_N \rangle = -\frac{G}{1 + G} \eta_E \langle I \rangle.
\]  

The corresponding normalized correlation coefficient \( C_{MN}^{(I)} \) is
\[
C_{MN}^{(I)} = \frac{\langle \delta I_M \delta I_N \rangle}{\sqrt{\langle \delta I_M^2 \rangle \langle \delta I_N^2 \rangle}} = -\sqrt{\eta_E}.
\]  

This shows that the anticorrelation between the quantum Poissonian-noise component and classical modulated-noise one in the LED (or LD) output intensity fluctuations is incomplete, its normalized correlation coefficient \( C_{MN}^{(I)} \) is only related to the photon emitting efficiency \( \eta_E \) of the LED (or LD). When \( \eta_E = 1 \), we obtain \( C_{MN}^{(I)} = C_{MN}^{(i)} = -1 \). This is an expected result in the quantum or semiclassical theory.

Using Eqs. (8)–(12), the total intensity fluctuations of the LED (or LD) output light are derived as
\[
\langle \delta I^2 \rangle = \langle (\delta I_M + \delta I_N)^2 \rangle = \langle I \rangle \left[ \frac{\eta_E}{(1 + G)^2} + 1 - \eta_E \right]
\]  

and the corresponding squeezing \( S^{(I)} \) of intensity fluctuations below the standard quantum limit (SQL) and its Fano faction \( F^{(I)} \) are given, respectively,
\[
S^{(I)} = 1 - \frac{\langle \delta I^2 \rangle}{\langle \delta I_N^2 \rangle} = \eta_E \left( 1 - \frac{1}{(1 + G)^2} \right)
\]  

\[ F^{(I)} = 1 - S^{(I)} = 1 + \eta_E \left[ \frac{1}{(1 + G)^2} - 1 \right] = \eta_E F^{(i)} + (1 - \eta_E). \]

When \( G = 0 \) \((F^{(i)} = 1)\) and \( \langle \delta I^2 \rangle = \langle I \rangle \), we obtain \( S^{(i)} = 0 \) and \( F^{(i)} = 1 \). This shows that when without the feedback resistance \( R \) (i.e., \( R = 0 \)), there is no squeezed effect in the LED (or LD) output light and its intensity fluctuations present Poissonian distribution. While the feedback gain \( G \) is large enough (that is, \( R \gg R_d \) and \( F^{(i)} \approx 0 \)), Eqs. (15)–(17) can be reduced, respectively, as
\[
\delta I^2 \approx \langle I \rangle (1 - \eta_E),
\]  

\[ S^{(i)} \approx \eta_E, \]  

and
\[ F^{(i)} \approx 1 - \eta_E. \]  

This shows that when \( G \gg 1 \), the intensity fluctuations of the LED (or LD) output light will be reduced below its SQL, its squeezing is about \( \eta_E \), which is consistent with the predicted results from both quantum and semiclassical theories [10,12,16], and also in good agreement with the experimental results [11,16,18–22].

4. Sub-shot-noise photocurrent

If the quantum collected and detected efficiencies of the photo-detector (PD) for the LED (or LD) output light are \( \eta_C \) and \( \eta_D \), the mean photocurrent \( \langle i_P \rangle \), and its quantum Poissonian-noise component \( \delta i_{PN} \) and the classical modulated-noise one \( \delta i_{PM} \) are given, respectively, by
\[
\langle i_P \rangle = \eta_C \eta_D \langle I \rangle = \eta \langle I \rangle,
\]  

\[ \delta i_{PM} = \eta_C \eta_D \delta I_M = \eta \delta i, \]  

and
\[
\langle \delta i_{PM}^2 \rangle = \eta_C \eta_D^2 \langle \delta I_N^2 \rangle + \eta_C \eta_D (1 - \eta_C \eta_D) \langle I \rangle.
\]  

Here, the first item is the inherent quantum Poissonian-noise component in photocurrent fluctuations from the quantum intensity noise one \( \delta I_N \) and the
second one is the quantum demolition-measurement-induced noise component because of the non-unity quantum collected and detected efficiencies of the PD ($\eta_C \eta_D < 1$). Whereas Eq. (22) shows that the classical photocurrent noise component $\delta i_{PM}$ results only from the classical intensity noise one $\delta I_M$ or from the classical modulated-noise one $\delta I_M$ in the photocurrent fluctuations. The corresponding correlation function $\langle \delta i_{PM} \delta i_{PN} \rangle$ and its normalized correlation coefficient $C_{MN}^{(i)}$ can be derived, respectively, as

$$\delta i_{PM}^{(i)} = \eta_C \eta_D \langle \delta I_M \delta I_N \rangle = -\eta^2 \frac{G}{1 + G} \langle i \rangle$$

and

$$C_{MN}^{(i)} = \eta \left\{ \frac{\delta i_{PM} \delta i_{PN}}{\langle \delta i_{PM}^2 \rangle^{1/2}} \right\} = -\sqrt{\eta} \eta_C \eta_D$$

This shows that the anticorrelation between the quantum Poissonian-noise component $\delta i_{PN}$ and classical modulated-noise one $\delta i_{PM}$ is only related to the total current conversion efficiency $\eta$ from the driven current into the photocurrent. When $\eta = 1$, $C_{MN}^{(i)} = -1$, this is a very natural result.

Using Eqs. (8) and (19), the fluctuation of the PD output photocurrent is given by

$$\langle \delta i_p^2 \rangle = \eta \left\{ \frac{\eta}{(1 + G)^2} + (1 - \eta) \right\} = \langle i \rangle \left\{ F(i)^2 + 1 - \eta \right\},$$

(26)

and the corresponding squeezing $S^{(i)}$ of photocurrent noise below the SNL and its Fano faction $F^{(i)}$ are given, respectively, by

$$S^{(i)} = \eta \left\{ 1 - \frac{1}{(1 + G)^2} \right\} = \eta (1 - F^{(i)})$$

(27)

and

$$F^{(i)} = 1 - \eta \left[ 1 - \frac{1}{(1 + G)^2} \right] = \eta F^{(i)+1} - \eta,$$

(28)

which is the same as Eq. (3) in Ref. [16], Eq. (8) in Ref. [19], and Eq. (1) in Ref. [25].

From Eqs. (27) and (28), when $F^{(i)} = 1$ (i.e., $G = 0$) and $\langle \delta i_p^2 \rangle = \langle i \rangle$, we obtain $S^{(i)} = 0$ and $F^{(i)} = 1$. This shows that there is no squeeze effect in the photocurrent fluctuations as the feedback resistance $R = 0$ (for a shot-noise-driven current source). While the feedback gain $G$ is large enough (that is, $F^{(i)} \approx 0$), Eqs. (26)–(28) can be approximated, respectively, by

$$\langle \delta i_p^2 \rangle \approx \langle i \rangle (1 - \eta),$$

$$S^{(i)} \approx \eta,$$

(29) and

$$F^{(i)} \approx 1 - \eta.$$

(30)

This shows that when $F^{(i)} \approx 0$ ($G = R/R_d \gg 1$), the fluctuations of the PD output photocurrent will be reduced below its SNL, its squeezing is about $\eta$, which is consistent with the theoretical and experimental results in Refs. [10,11,16,18–22].

5. Calculation results and comparisons

As an applied example, we calculated the relationship between the squeezing of the photocurrent noise and the normalized pump rate $r = \langle i \rangle / \langle i_{th} \rangle - 1$ in a strained-layer multi-quantum well DFB laser diode with the emitting wavelength $\lambda = 1.3$ mm. When $T = 300$ K, the threshold current $\langle i_{th} \rangle = 8.8$ mA, the pumping rate $r = 0–10$, and the total quantum conversion efficiency $\eta$ is shown as in Fig. 4(a) of Ref. [26], the normalized photocurrent noise versus the pump rate is shown in Fig. 4. It is clear from Fig. 4 that when $R > 0$ and $r > 0$, the photocurrent fluctuations will be reduced below the SNL, and its squeezing will be increased with the pump current $I$, or with the feedback resistance $R$, which is in good agreement with the quantum calculated results of Chang et al. [26], and also similar to the results from other quantum theory [10,14] when the pumping rate $r \geq 0$. However, there is not a simple and analytical expression to directly describe the relationship between the intensity noise spectral density $S$ and the pump rate $r$ in quantum theory. So to obtain this function relation, they had to do some numerical calculations and analysis.

By using our semiclassical model (see Eqs. (27) and (28)), we also calculated the relationship between the Fano faction $F^{(i)}$, or the squeezing of the photocurrent noise $S^{(i)}$, and the series-coupled
source resistance \( R \), which are shown in Figs. 5(a) and (b), respectively. When \( R = 0 \) (i.e., \( G = 0 \)), or \( R \gg R_d (= 10 \Omega) \), and \( \eta = 0.3, 0.5 \) and 0.9, we obtain \( F^{(ip)} = 1 \) (it presents the SNL), or 0.7, 0.5 and 0.1 (i.e., \( F^{(ip)} = 1 - \eta \)) from Fig. 5(a), and have \( S^{(ip)} = 0 \) or 0.3, 0.5 and 0.9 (i.e., \( S^{(ip)} = \eta \)) from Fig. 5(b), which are consistent with the results from the semiclassical theory [2–6,16,18,19]. However, our semiclassical model give a simple and complete expression to describe the Fano factor, or the squeezing of photocurrent noise as a function of the source resistance \( R \) (or the feedback gain \( G \)) within \( R = 0–\infty \) (including \( R \gg R_d \)); whereas nearly all of conventional semiclassical theories [2–6,18,19] can only give two values of the Fano factor \( F^{(ip)} \), or the photocurrent-noise squeezing \( S^{(ip)} \) under two limit cases of \( R = 0 \) and \( R \gg R_d \).

In addition, in both quantum and conventional semiclassical theories, one also thinks that the generation of photon-number squeezed light in the HICC-driven LED (or LD) originates from the compression of pump-current noise, whereas this pump-noise suppression results from the negative self-feedback effect of a source resistance \( R \) in series with the LED (or LD), so sub-Poissonian pump current is converted into sub-Poissonian light by a high-efficient LED (or LD). This noise-squeezed mechanism shows that the negative feedback action of a series-coupled source resistance \( R \) plays an important role in the generation of amplitude squeezed light in the LED (or LD). But in the theoretical treatment, quantum theory derives the amplitude (or photon number) noise spectral density from the generalized master equation, or from the quantum Langevin equations [10,13,14,27,28]; whereas the treatment of semiclassical theory starts from adiabatic elimination and rate equations [6,15–17,19]. We can see from here that there is not an inevitable or a direct connection between the real noise-squeezed mechanism and theoretical treatment model in both quantum and semiclassical theories. However, in our new semiclassical model, we directly derive the relationship between the Fano factor, or the squeezing of intensity (or
photocurrent) fluctuations and the feedback gain $G$ (or the source resistance $R$) from the real noise-squeezed mechanism based on the negative self-feedback action of the series-coupled source resistance $R$ in the HICC-driven LED (or LD) circuit. So our semiclassical model is not only simple and convenient, but the physical picture (see Fig. 3) is also very clear and intuitive, which will help one to easily understand the suppression mechanism of quantum noise in the HICC-driven LED (or LD).

6. Conclusions

We have proposed a new and simple semiclassical model to analyze sub-Poissonian light and sub-shot-noise photocurrent in HICC-driven LEDs (or LDs), and obtained some new and interesting results. Our study shows that (1) when without considering the influence of Johnson–Nyquist thermal noise on the driven current, the anticorrelation between the quantum Poissonian-noise component and classical modulated-noise one in the pump-current fluctuations is complete, which results in deep suppression of the pump-current noise; (2) the anticorrelated pump-current noise gives rise to an anticorrelated intensity fluctuations, and then results in the generation of an amplitude squeezed light (that is, a sub-Poissonian light). However, the anticorrelation between the quantum Poissonian-noise component and classical modulated-noise one in the intensity fluctuations is incomplete due to the non-unity quantum emitting efficiency of the LED (or LD); (3) similarly, the anticorrelated intensity noise leads to an anticorrelated photocurrent fluctuations, which gives a sub-shot-noise photocurrent. Because the quantum converted efficiency is non-unity, the anticorrelation between the quantum Poissonian-noise component and classical modulated-noise one in the photocurrent fluctuations is also not complete, and its correlation coefficient and squeezing of photocurrent noise will be determined by the quantum converted efficiency and the feedback gain $G$ (i.e., feedback resistance $R$).

With our new semiclassical model, moreover, we obtain a simple and complete analytical expression to describe the relationship between the Fano factor $F$, or the squeezing $S$ of quantum noise and the feedback gain $G$ (or series-coupled source resistance $R$), which are consistent with ones from quantum models and other semiclassical models at low points of $G = 0$ (i.e., $R = 0$) and $G \gg 1$ (i.e., $R \gg R_d$). That is, the above analytical expression has not been derived from other semiclassical theory or quantum theory. In addition, our derivation starts from a real noise-suppression mechanism based on the negative self-feedback effect of the series-coupled source resistance $R$ in the LED (or LD) circuit. So our model proposed here gives a simple and distinct physical picture to explain the squeezed mechanism of intensity fluctuation in HICC-driven LED (or LD), and can be applied to study Johnson–Nyquist thermal-noise effect [16], quantum-noise correlation [13,19,26] in series- or parallel-coupled LED (or LD) system, electronic partition-noise effect [29], optical feedback effect [30] and injection-locked effect [31] as well as quantum correlation between longitudinal-mode intensities in multi-mode squeezed LD [32], and so on.

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