Photon statistics of semiconductor laser diodes

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Outline

1  Photo statistics
   ■ Photo detection
   ■ Super and sub-Poissonian light

2  Light-emitting semiconductor diodes
   ■ Injection electro-luminescence
   ■ Sub-Poissonian light generation

3  Outlook
Photo detection
Available methods

Direct photon counting
Requires high quantum efficiency at low intensity (e.g. photomultiplier)

Indirect reconstruction
Requires high quantum efficiency at high intensity (e.g. PIN photo diode)

1. Phase-integrated balanced homodyning
2. Full quantum-state reconstructions:
   - Balanced homodyne tomography
   - Cascaded homodyne reconstruction
Atoms are potential emission centers of photo-electrons

Photo-electrons are multiplied to a macroscopic electrical photo-current
Photo detection
Photons versus photo-electrons

\[ W_n = |\langle n | \psi \rangle|^2 \]

Photo-ionization is a probabilistic process:
- Photon and photo-electron statistics are different: \( W_n \neq P_n \)
- Only a fraction of photons are converted to photo-electrons:
  \[ \overline{m} = \eta \cdot \overline{n} \]
  with quantum efficiency \( 0 \leq \eta \leq 1 \)
Photo detection

Mandel photo-counting formula

Probability to observe \( m \) photo-electrons in the time interval \([t, t + T_D]\):

\[
P_m(t, t + T_D) = \left\langle \frac{\left[ \eta \hat{N}(t, t + T_D) \right]^m}{m!} e^{-\eta \hat{N}(t, t + T_D)} \right\rangle
\]

where the integrated number of arriving photons is:

\[
\hat{N}(t, t + T_D) \propto \sum_i \int_{t}^{t + T_D} d\tau \hat{E}^(-)(r_i, \tau) \cdot \hat{E}^+(r_i, \tau)
\]

\( T_D \) is the characteristic integration time of detector and electronic amplification:

\[ 0, \ldots, f_D = 1/T_D \] is the bandwidth of the photo detector.
Photo detection
Coherence time vs. detector integration time

\[ T_D > T_C \]

Slow detector: \( T_D > T_C \)

- Photo-electron statistics is always Poissonian:

\[
P_m = \frac{[\eta\langle \hat{N} \rangle]^m}{m!} e^{-\eta\langle \hat{N} \rangle}
\]

Fast detector: \( T_D < T_C \)

- Information on photo statistics is contained
- Bandwidth of detector must be larger than light linewidth
Super and sub-Poissonian light

Mandel Q parameter

Poissonian statistics

\[ P_n = \frac{\bar{n}^n}{n!} e^{-\bar{n}} \]

Special relation in this case for RMS spread:

\[ \Delta n = \sqrt{\bar{n}}. \]

Mandel Q parameter

\[ Q = \frac{\Delta n^2 - \bar{n}}{\bar{n}} = 0 \]

In case of \( \Delta n \gtrless \sqrt{\bar{n}} \): \( Q \gtrless 0 \)

- \( Q > 0 \): Super-Poissonian photo statistics
- \( Q < 0 \): Sub-Poissonian photo statistics
- \( Q = 0 \): Poissonian photo statistics (coherent laser light)
Super and sub-Poissonian light

Bunching vs. anti-bunching of photons

Anti-Bunching

"Normal"

Bunching

$Q = 0$

$Q < 0$

$Q > 0$

Poissonian

Sub-Poissonian

Super-Poissonian
Injection electro-luminescence

Band model
Injection electro-luminescence

Output photon flux

Output photon flux for a given forward-bias current $I$:

$$\Phi = \eta_e \eta_i \frac{I}{e}$$

Electron-photon conversion efficiency:

- **Internal quantum efficiency**

  $$\eta_i = \frac{\gamma_r}{\gamma_r + \gamma_{nr}}$$

  with (non-)radiative recombination rate $\gamma_r$ ($\gamma_{nr}$)

- **Overall transmission efficiency** $\eta_e$:
  - internal absorption
  - multiple reflections
Sub-Poissonian light generation
Light-emitting diode (LED)

Constant current injection with high efficiency ($\eta_e \eta_i \sim 1$):
- Current statistics transforms into photon statistics
- Current statistics is sub-Poissonian (Johnson noise)
Sub-Poissonian light generation

Johnson current noise

Shot-noise limit ( = Poissonian variance) vs. actual Johnson current noise:

\[ \langle \Delta I^2 \rangle_{sn} = 2eI \cdot \Delta f; \quad \langle \Delta I^2 \rangle = \frac{4k_B T}{R} \cdot \Delta f \]

Reduction of current noise below shot-noise limit if:

\[ I > \frac{2k_B T}{eR} \approx \frac{52\text{mV}}{R} \quad (T \approx 300\text{K}) \]

Resulting \( Q \) parameter for perfect current noise suppression:

\[ Q \approx -\eta_e \eta_i \]

Problem: Collection and detection of light
Sub-Poissonian light generation
Laser diode: current regulation by negative feedback

For small active region and low temperature additionally: **Coulomb blockade**
Outlook

What has not been considered so far:

- Dressed-state picture: potential barrier for electron when entering the interaction zone
- Additional effects like in the micro-mazer
- Micro-mazer type solvable model in semi-classical approximation