Fundamental noise mechanisms in semiconductor oscillators and amplifiers

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✔ Fighting against line perturbation starts at the early age of communication
✔ What, by those days, about optical signals?
Outline

1. Intrinsic fluctuations of optical signals
2. Noise and stabilization mechanisms in a SCL
3. Intensity noise
4. Semiconductor laser line width
5. Squeezed states of light
6. Conclusion

A Classical Corpuscular Approach: Shot Noise

Random arrival times

Random number during the observation time $\tau$

$\langle (\Delta n)^2 \rangle = \langle n \rangle$ Poisson fluctuations

Bandwidth/ integration time $\tau = 1/2B_e$

Equivalent fluctuations of optical power $P = \frac{nhv}{\tau}$

$\delta P^2 = 2\hbar v < P > B_e$ Optical Schottky relation

Fluctuations of optical power

$I = \frac{n^e}{h\nu} P$

$\langle \delta I \rangle^2 = 2e < I > B_e$ Electrical Schottky relation
Coherent v.s. Incoherent Light

✔ Chaotic light

\[ p(t) = \frac{1}{\langle f \rangle} \exp\left( \frac{f(t)}{\langle f \rangle} \right) \delta f = \langle f \rangle \]

Bunch

✔ Bose-Einstein

\[ p(n) = \frac{\langle n \rangle^n}{[1 + \langle n \rangle]} \quad \langle \Delta n^2 \rangle = \langle n \rangle + \langle n \rangle^2 \]

particle

Wave

✔ Poisson

\[ p(n) = \frac{\langle n \rangle^n}{n!} \exp(-\langle n \rangle) \quad \langle \Delta n^2 \rangle = \langle n \rangle \]

What About the Fluctuations of Optical Amplitude?

✔ Single polarization

✔ Power \( <P> = (\text{Amplitude})^2 = A^2 \)

✔ Additive Gaussian noise \( N \)
  - Uncorrelated “in phase” and “quadrature” components
  - Sharing of total noise power
    \[ P_N = P_1 + P_0 \quad \text{and} \quad P_i = P_0 \]
  - \( N_i \) and \( N_2 \) are baseband process

✔ Instantaneous power fluctuations

\[ P = (A + N_i)^2 = <P> + 2AN_i + N_i^2 \]

✔ Mean square value

\[ (\delta P)^2 = <\Delta P^2> = 2 <P> P_N = \Delta P \]

Power fluctuations are the double cross-term (beating) between the signal amplitude and the in-phase noise.
What is the Amplitude Noise Producing the Shot Noise?

- Shot noise: \((\delta P)^2 = 2\hbar \nu < P > B_s\)
- Gaussian additive noise: \((\delta P)^2 = 2 < P > P_N\)
- Single sided spectral density
  - Single polarization

\[ S_{N0} = \frac{\hbar \nu}{2} \]

- \(S_{N0} = 0.65 \times 10^{-19} \text{ J (or W/Hz)} = -162\text{dBm/Hz(optical)} \) @ \(\lambda = 1.5\mu\)
- Half the photon energy
- Not directly observable
- Their cross term with the signal is the shot noise

So-called “Zero-Point Fluctuations” or “Vacuum Fluctuation”

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Vacuum Fluctuations

- Vacuum fluctuations are independent of the signal
  - They exist without signal
- Vacuum fluctuations are non elusive
  - Already present at any (evenly unused or hidden!) optical input
- Vacuum fluctuation are a blue noise

\[ S_{N0} = \frac{\hbar \nu}{2} \]

- Optical circuit are strongly resonant (band pass)
- Noise power remains proportional to the bandwidth
- The minimum energy of any quantized harmonic oscillator

\[ E_n = \left(n + \frac{1}{2}\right)\hbar \nu \quad E_0 = \frac{\hbar \nu}{2} \text{ for } n = 0, \]

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What About Phase Fluctuations?

- Phase fluctuations
  \[ \Delta \varphi \approx \frac{N_Q}{A} \]
- Mean squared power fluctuations
  \[ (\delta \varphi)^2 = P_N / 2 < P > \]
- Conjugation
  \[ \delta P \delta \varphi = P_N \]

- Equivalent to the phase-number Heisenberg relation
- Independent of the signal!
- Valid even there is no signal!

- Photon number received during \( \tau \)
- Time-bandwidth relation
  \[ B_e = 1/2 \tau \]

State with minimum indeterminacy

- Vacuum fluctuation
  \[ \delta E_i = \delta E_2 = E_{\text{EFF0}} \]
  \[ \delta E_i, \delta E_2 = E_{\text{EFF0}}^2 \]
- Etat Quasi-Classique ou cohérent
  \[ \delta E_i = \delta E_2 = E_{\text{EFF0}} \]
  \[ \delta E_i, \delta E_2 = E_{\text{EFF0}}^2 \]
- Other scaling
  \[ \Delta n^2 \approx \frac{1}{2} \]
  \[ \langle \Delta n \rangle = \langle n \rangle \]
Quantification of the electromagnetic field

\[ p, q \rightarrow \hat{p}, \hat{q} \]
\[ E, H \rightarrow \hat{E}, \hat{H} \]

\textit{MAXWELL} \rightarrow \textit{MAXWELL!}

\textit{ELECTROMAGNETISM} \rightarrow \textit{QUANTUM ELECTRODYNAMIC}

✔ Consequences

- Same modes
- Quantified Energy
- Quantum fluctuation
- Amplitude of probability

\[ \epsilon_n = n + \frac{1}{2} \]
\[ h \nu \neq 0 \]

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Conjugated Variables

✔ Commutator:

\[ \left[ \hat{A}, \hat{B} \right] = jh = j\frac{\hbar}{2\pi} \]

✔ Heisenberg indeterminacy (and not uncertainty) relationship

\[ \delta A^2 \delta B^2 \geq \frac{1}{4} \left\langle \left[ \hat{A}, \hat{B} \right] \right\rangle^2 = \frac{\hbar^2}{4} \]

✔ Examples: \((E,t), (p,\nu,\chi), (p,q)\)

✔ It is a conséquence of the wave nature

\[ \delta E. \delta t \approx \frac{\hbar}{2} \]

\[ \frac{E = h\nu}{\text{Planck}} \quad \delta \nu. \delta t \approx \frac{1}{4\pi} \]

\[ \text{Heisenberg} \quad \text{Parceval} \]

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Quantum Mechanics  Point of View

✔ Normal order \( \langle \Delta \hat{a} \Delta \hat{a}^* \rangle = 1 \),

✔ Weyl's order \( \langle \Delta \hat{a}^* \Delta \hat{a} \rangle = 0 \)

✔ The non Hermitian photon annihilation quantum operator and its adjoint is the photon creation operator are respectively the in-phase and a quadrature components

\[
\hat{E}(t) = \sqrt{\frac{h \nu}{T}} \left[ \hat{a}(t) \exp j \omega_0 t + \hat{a}^*(t) \exp -j \omega_0 t \right] - 2 \sqrt{\frac{h \nu}{T}} \left[ \hat{a}(t) \cos \omega_0 t - \hat{a}^*(t) \sin \omega_0 t \right]
\]

✔ Symetrisation of the Hermitian operator

\[
\frac{1}{2} \langle \Delta \hat{a} \Delta \hat{a}^* + \Delta \hat{a}^* \Delta \hat{a} \rangle = \frac{1}{2}
\]

- canceling out the commutator contributions
- equivalent of the classical total noise power
- but is not directly observable

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**Fluctuation Dissipation Theorem**

\[ P_{\text{IN}} \quad \delta \phi_{\text{IN}} \quad G \quad \delta P_{\text{OUT}} = G \delta \quad \delta \phi_{\text{OUT}} = \delta \phi_{\text{IN}} \]

- Ideal linear phase insensitive amplifier
  - G is the power gain
  - Signal and power fluctuations amplification
  - Possible phase shift
  - Phase fluctuations unchanged
- Possible output measurement fulfilling
  \[ \delta P_{\text{OUT}} \delta \phi_{\text{OUT}} = P_N \]
- Equivalent input measurement
  \[ \delta P_{\text{IN}} \delta \phi_{\text{IN}} = P_N / G \]
- Heisenberg uncertainty principle violation

**Nyquist Theorem for Thermal Noise**

\[ I = \frac{V}{R} + \Delta I \quad N_0 = kT \]

- Signal response (Dissipation)
  - Macroscopic
  - Deterministic
  \[ I^2 = \frac{2VI}{R} = \frac{2P}{R} \]
- Noise (Fluctuation)
  - Microscopic
  - Square average
  \[ \langle (\Delta I)^2 \rangle = \frac{2P_N}{R} \]
- The same resistance \( R \)
  - For the deterministic part (dissipation)
  - The averaged fluctuating part of the signal
- Link between microscopic and macroscopic
- Valid for loss \( R > 1 \) or gain \( R < 1 \)
Spectral densities of Added Noises

✔ Noise addition is mandatory (H. Heffner)
  ❑ To preserve uncertainty principle
  ❑ To preserve bracket commutator

$$S_{\text{ADDED}} = |G - 1| \frac{h\nu}{2}$$

✔ Origin of added noise (H. Haus)
  ❑ Electron momentum fluctuations
  ❑ Stimulation by vacuum fluctuations

✔ Single sided spectral density of added noise

Amplification $G > 1$

$$S_{\text{ADDED}} = (G - 1) \frac{h\nu}{2}$$

Attenuation $A < 1$

$$S_{\text{ADDED}} = (1 - A) \frac{h\nu}{2}$$

Noise with Distributed Amplification and Loss

✔ Slice $dz$ of medium

$$dS_n = (\beta - \alpha)S_n dz + \left[(\beta + \alpha)(h\nu/2)dz\right]$$

✔ Integration over a length $L$ with vacuum fluctuation input

$$S_n(L) = \left[\frac{\alpha + \beta}{|\beta - \alpha|} (G - 1) + G\right] \frac{h\nu}{2}$$

✔ Spontaneous emission interpretation

$$S_n(L) = \left[2n_{sp}(G - 1) + 1\right] \frac{h\nu}{2}$$

$$n_{sp} = \frac{G}{\beta - \alpha} \frac{\text{gain}}{\text{gain - loss}} = \frac{N_2}{N_1}$$

$n_{sp}$ is the population inversion factor
A Straightforward but Formal Derivation 1/2

✓ Heisenberg uncertainty are linked to commutators
\[ \langle \Delta X^2 \rangle \langle \Delta Y^2 \rangle = \Delta X^2 \Delta Y^2 \geq \frac{1}{4} \left\langle \left[ X Y \right] \right\rangle \]
\[ \hat{\Delta X} \hat{\Delta Y} = \hat{X} \hat{Y} - \hat{Y} \hat{X} \]

✓ Input to output relation for the two quadratures in the form:
\[ \begin{bmatrix} X \\ Y \end{bmatrix}_{\text{OUT}} = \begin{bmatrix} \sqrt{G} & 0 \\ 0 & \sqrt{G} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}_{\text{IN}} \]
\[ \left\langle [X_{\text{OUT}}Y_{\text{OUT}}] \right\rangle = G \left( [X_{\text{IN}}Y_{\text{IN}}] \right) \]

Do not preserves input commutators in the output (except for G = 1!)

✓ The input to output relation must be in the form
\[ \begin{bmatrix} X \\ Y \end{bmatrix}_{\text{OUT}} = \begin{bmatrix} \sqrt{G} & 0 \\ 0 & \sqrt{G} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}_{\text{IN}} + \begin{bmatrix} N_x \\ N_y \end{bmatrix} \]

Added noise

✓ Output commutator is written as
\[ \left\langle [X_{\text{OUT}}Y_{\text{OUT}}] \right\rangle = G \left( [X_{\text{IN}}Y_{\text{IN}}] \right) + \left\langle N_x N_y \right\rangle + \sqrt{G} \left( [X_{\text{IN}}N_y] \right) + \sqrt{G} \left( [N_x Y_{\text{IN}}] \right) \]

Last 2 terms vanish out through ensemble average
A Straightforward but Formal Derivation 2/2

✔ Preservation of commutator is written as:

\[ \langle [N_X, N_Y] \rangle = (1 - G) \langle [X, Y] \rangle \]

✔ The corresponding uncertainty relation is

\[ \delta N_X^2 \delta N_Y^2 \geq |G - 1|^2 (\delta X_N^2 \delta Y_N^2)_{\text{MINIMUM}} \quad \delta X^2 \delta Y^2 \geq \frac{1}{4} \left( \langle [X, Y] \rangle \right)^2 \]

✔ The corresponding noise power relation is

\[ P_A \geq |G - 1| P_{N_{\text{MINIMUM}}} = |G - 1| \frac{h \nu}{2} B_0 \quad \delta X^2 \delta Y^2 = P_{X} P_{Y} = \frac{P}{4} \]

✔ For an amplifier G > 1

\[ P_A \geq (G - 1) \frac{h \nu}{2} B_0 \]

✔ For attenuation G = A < 1

\[ P_A \geq (1 - A) \frac{h \nu}{2} B_0 \]

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Noises Sources, Rejection and Filtering

✔ Fundamental noise sources

- Zero-point fluctuations (vacuum fluctuations)
- Noise related to absorption and stimulated emission
- Noise related to mirror(s) losses

✔ Technical noises

- Thermal fluctuations and drift
  - Stabilization: \( \Delta T = 10^{-2} \) to \( 10^{-3} \) K
- Technical fluctuations of the injected current
  - Rejected by population inversion for homogeneous gain saturation
  - Stabilization required otherwise
- Partition noise for multimode structure
- Polarization noise
- Filamentation for weak transverse guiding
- 1/f surface noise...

✔ Noise filtering

- Exaltation at the relaxation frequency
- Noise rejection below
Gain Saturation v.s. Gain Compression

Gain saturation
- Stabilization when stimulated recombination are compensated by the pump
- For frequencies lower than the interband relaxation frequency ($<10^{-10}$ s)

Gain compression
- Spatial hole burning
- Spectral hole burning
- Carrier heating
- Very fast ($10^{-12}$ s) because of its intraband origin

$G = \text{gain per unit of time}$
$N = \text{carrier number}$
$P = \text{photon number in the mode}$

$G(N) = A(N - N_0)$
$G(N) = A(N - N_0)(1 - \varepsilon P)$

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Stochastic Rate Equations (Mc Cumber)

- Stochastic rate equations (Mac Cumber)
  - Photon number $P$
    - $\tau_P$: Photon lifetime in the cold cavity
  - Carrier number $N$
    - $\tau_E$: Spontaneous electron lifetime
  - Output photon rate $\rho$
    - $\tau_M$: Photon lifetime linked to mirror(s) losses

- Correlated Langevin noise forces
  - $F_P(t) = f_p(t) + f_x(t)$
    - $f_p(t)$: current noise + spontaneous recombinations
    - $f_x(t)$: noise associated to amplification
  - $F_N(t) = f_p(t) - f_x(t) + f_p(t)$
    - $f_p(t)$: noise associated to resonant absorption
    - $f_x(t)$: noise associated to mirror(s) losses
  - $F_\rho(t) = f_p(t)$
    - $f_p(t)$: noise associated to internal losses

- Anti correlations provide stabilization
  - Except for internal, current and spontaneous recombination noise...

Equation Solving

- Method
  - System linearization for $P, N, \rho$:
    $$X(t) = \bar{X} + \delta X(t)$$
  - Fourier transforms:
    $$\delta X(t) \rightarrow \delta \hat{X}(\omega)$$
  - Spectra calculation:
    $$S_{XY}(\omega) = \left(\delta \hat{X}(\omega)\delta \hat{Y}(\omega)\right)^*$$

- Results:
  - Internal noise: $S_{pp}(\omega)$
  - External noise: $S_{pp}(\omega)$
  - Voltage noise: $S_{NN}(\omega)$
  - Voltage - Output power correlation: $S_{\rho\rho}(\omega)$
Noise Attenuation

- Noise propagation equation
  \[ dS_N = -\alpha S_N dz + \left[ \alpha (h\nu/2) dz \right] \]
- Integration over a length \( L \) with boundary condition \( S_N(0) \)
  \[ S_N(L) = [S_N(0) - (h\nu/2)] \exp(-\alpha L) + h\nu/2 \]
- The excess of noise vanishes out through attenuation
- Vacuum fluctuation is a noise floor
  - Attenuation noise generation counteracts the input noise attenuation
  - Only the signal is attenuated
- The intensity noise of any attenuated signal turns to shot noise

Shot Noise Level

- Averaged photo current proportional to the optical power \( P \)
  \[ I = RP \quad R = \eta e/h\nu \]
  - \( R \) is the photo receiver sensitivity in (A/W)
- For \( \eta \) close to 1 the photon noise is cloned into electron noise
  \[ (\delta P)^2 = 2h\nu < P > B_x \quad I = RP \quad (\delta I)^2 = 2\eta e < I > B_x \]
- Shot noise level
  - Easy to calibrate: directly related to DC current
  - Function of the optical power
  - Electrical power spectral density equal to -138dBm/Hz
    - for a 0dBm optical power @ \( \lambda = 1.5\mu m \) \( R = 1A/W \), \( R_L = 50 \Omega \)
  - To be compared to \( 4kT = -175dBm \) (+noise figures) @ \( T=300K \)
- Power noise floor for classical signals
Relative Intensity Noise (RIN)

The usual definition (G. Agrawal)

\[ RIN(\omega) = \frac{S_{pp}(\omega)}{<P>} = \frac{S_{\nu}(\omega)}{<I>} \]

- Internal and external noises are different
- Depends on optical attenuation
- All the light must be collected
- Problem for power laser
- The shot noise level is the floor

✔ Power level to be mentioned
✔ Usually expressed in dB/Hz

\[ RIN(\omega) = \frac{2\nu}{<P>} = \frac{2e}{<I>} \]

- Shot noise level is used floor
- Independent of attenuation
- Minimum is zero for classical states
- Negative for intensity squeezed states

\[ RIN(\omega) = \frac{S_{\nu}(\omega) - 2e <I>}{<I>} \]

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A. Schawlow and C. Townes

✔ No restoring force for the phase
✔ Cold cavity bandwidth
\[ \Delta \omega = \frac{1}{\tau_P} \]
✔ Hot cavity bandwidth
\[ \Delta \omega = \frac{1}{2} \left( \frac{1}{\tau_P} - G \right) \]

❑ Gain loss compensation
❑ Half of noise power
✔ Averaged rate equation
\[ 0 = \left( G - \frac{1}{\tau_P} \right) P + R \]

❑ Spontaneous emission rate
\[ R = \langle F_p(t) \rangle \]
\[ \text{Stimulated emission} = \frac{1}{P} \frac{R}{GP} \]
\[ \Delta \omega = \frac{R}{2P} = \frac{n_{\omega} G}{2P} \approx \frac{n_{\omega} G}{2 \tau_P} \]

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(M. Lax) C. Henry Factor

\[ \Delta n' \text{ and } \Delta n'' \text{ related by the Kramers-Krönig relations} \]
\[ \Delta n' = 0 \text{ for the maximum of differential gain i.e for minimum } \Delta n'' \]
\[ \Delta n'' = \frac{\partial n'}{\partial N} \Delta N \]

The laser operate at the maximum gain value and is detuned toward larger wavelength
\[ \frac{\Delta \varphi}{\Delta [E/E]} = \frac{\Delta n'}{\Delta n''} = \alpha_H \]
\[ \alpha_H \text{ is in the few unit range} \]

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Single Mode Laser Line Width -1

✔ Phase diffusion
  ❑ The spectral width is the rate of diffusion
  ❑ Frequency noise is white
✔ Addition of a spontaneous photon

Direct action

\[
\Delta \varphi = \frac{1}{\sqrt{P}} \sin \theta_i
\]

\[
\langle \Delta \varphi_i \rangle = \frac{1}{2P}
\]

Phase amplitude coupling action

\[
\Delta \varphi = \frac{1}{\sqrt{P}} (\sin \theta_i - \alpha \cos \theta_i)
\]

\[
\langle \Delta \varphi_i \rangle = \frac{1}{2P} (1 + \alpha \alpha_i)
\]

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Single Mode Laser Line Width - 2

✔ With \( R \tau \) spontaneous photons during \( \tau \)

\[
\langle \Delta \varphi^2(\tau) \rangle = \frac{n_s \sigma \tau}{2 \tau P} (1 + \alpha \alpha_i)
\]

✔ The mean square of the phase jitter increases linearly with \( \tau \)
  ❑ Brownian motion
  ❑ The spectrum is a Lorentzian function
  ❑ The total spectral width at half maximum (FWHM)

\[
\Delta \omega_L = \frac{n_s \sigma \tau}{2 \tau P} (1 + \alpha \alpha_i)
\]

❑ A. Schawlow and C. Townes
❑ Frequency drift are not expressed by that
✔ When \( P \) increases
  ❑ The relative weight of the spontaneous emission decreases
  ❑ The spectral width decreases
✔ 0.1 to 100Mhz/mW depending on power and Q of the cavity

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Squeezing

✓ Equipartition of power noise is only default setting
  ❑ Entropy maximization
✓ Quantum mechanics only require a minimum product
  ❑ Equipartition can be changed

\[ \delta \phi \delta P = \frac{\hbar \nu}{2} B_0 \]

QUANTUM FLUCTUATIONS
Squeezed-States (Non-Classical States) of Light

- Coherent state
- Classical state
- Amplitude fluctuation
- Phase fluctuation
- Non-classical states

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Squeezed State Generation Using Semiconductor Laser

- Technical noises (vibrations, thermal and current fluctuations...) suppression or correction
- Below shot noise current injection
  - Easily obtained for charged electron (Fermions) : Charged space effect
- No storage capacity
  - i.e. for I = 10mA
- Electron noise cloning into photon noise
- Mirror(s) losses and resonant absorption have no influence
- High quantum efficiency i.e. no random photon killing without feed back
  - Low non radiative recombination
  - Low internal losses

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Bakery in Paris, 202, rue de Tolbiac

- Random customer arrivals (noisy current source)
- Queuing on the pavement
- Customers in an hurry go to an other bakery (charged space effect)
- Very small room inside (small carrier storage)
- Regulated customer entrance (low noise current injection)
- No customers disappear (high quantum efficiency conversion)
- Time inside only determined by seller girl (stimulated carrier life time)
- Time regulated output of customers (with bread)

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Neo Classical Description

Shot noise current injection

- Poissonian disorder
  \( \langle (\Delta n)^2 \rangle = \langle n \rangle \)
- Two sided spectral density of number fluctuations inside the laser
  - For high power and low non radiative recombination rate
  - For low frequency \( (\omega = 0) \)
  \( S_{pp}(0) = 2 \langle P \rangle \tau_p \)
- Two sided spectral density of the emitted photon flow
  \( S_{pp}(0) = \rho \)
  \( S_{pp}(0) = \rho(1 - \tau_p / \tau_m) = \rho(\tau_p / \tau_m) \)
- Shot noise level

below shot noise current injection

- Sub Poissonian fluctuations
  \( \langle (\Delta n)^2 \rangle < \langle n \rangle \)
- Low internal losses turns to shot noise reduction

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Achieving a Below Shot Noise Injection

✔ Current generator
   - \( R >> R_L \)
   - \( V_L \) may fluctuates
   - \( N \) may fluctuates
   - \( I \rightarrow V_R \rightarrow V_L \rightarrow N \rightarrow \)

- Counteraction to \( I \) fluctuations
- Space charge effect

✔ Voltage generator
   - \( R << R_L \)
   - \( V_L \) is constant
   - \( N \) is constant
   - No regulation

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Vertical Cavity Surface Emitting Laser (VeSCELs)

- Wavelength scale optical mode
  - Short optical cavity (2 to 10 μ)
  - Strong reflectivity DBR \( R = 98 \%
  - Possible metal rear mirror
  - High Q cavity/low line width/
  - Photon life time may be larger than the carrier one
  - Possible relaxation less operation
  - Single longitudinal mode operation
  - 3D confinement
- Weak polarization control
- Electrical characteristics
  - Low threshold
  - Long output mirror: 12 μm (InP/InGaAsP) to 6 μm (GaAs)
  - High resistivity
  - High relaxation frequency: 40Gbit/s reported
  - Low energy/bit: 100fs/bit

Conclusions

- Optical field are intrinsically fluctuating
- Attenuation and amplification are noisy process
- Spontaneous emission is produced by the 2 firsts
- Shot noise may be achieved
  - at low frequency
  - in high power regime
- Line with results of phase diffusion
- Below shot noise operation my be achieved in SCL
- Technical noise impair fundamental limits
  - Thermal fluctuation and drift
  - Partition noise for multimode structure
  - Polarization noise
  - Filamentation for weak transverse guiding
  - 1/f surface noise
- Terahertz range to explored \( T > \frac{hv}{k} \)
Generalized Nyquist Theorem

- Total single spectral density of radiation
  \[ N_0 = \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1} + \frac{h\nu}{2} \cdot \frac{h\nu}{2} \cdot \coth\frac{h\nu}{2kT} \quad \begin{cases} N_0 = \frac{h\nu}{2} & \text{for } h\nu \gg kT \\ N_0 = kT & \text{for } kT \gg h\nu \end{cases} \]

- Two sided power spectral density of current fluctuation
  \[ S_\nu = \frac{2N_0}{|R|} = \frac{h\nu}{|R|} \cdot \coth\frac{h\nu}{2kT} \quad \begin{cases} S_\nu = \frac{h\nu}{|R|} & \text{for } h\nu \gg kT \\ S_\nu = \frac{2kT}{|R|} & \text{for } kT \gg h\nu \end{cases} \]

I thank you for the quality of your attention!