Photon Number Squeezed States in Semiconductor Lasers

YOSHIHISA YAMAMOTO, SUSUMU MACHIDA, WAYNE H. RICHARDSON

Electromagnetic fields, with the noise on one quadrature component reduced to below the quantum mechanical zero-point fluctuation level and the noise on the other quadrature component enhanced to above it, are currently of great interest in quantum optics because of their potential applications to various precision measurements. Such squeezed states of light are usually produced by imposing nonlinear unitary evolution on coherent (or vacuum) states. On the other hand, squeezed states with reduced photon number noise and enhanced phase noise are generated directly by a constant current–driven semiconductor laser. This is the simplest scheme for the generation of nonclassical light, and so far it has yielded the largest quantum noise reduction. The mutual coupling between a lasing junction and an external electrical circuit provides opportunities for exploring the macroscopic and microscopic quantum effects in open systems.

INVESTIGATIONS OF THE STATISTICAL PROPERTIES OF RADIAtion lighted a path to the quantum theory. Quantum statistical properties of laser light have been extensively studied during the last 30 years. A laser is a nonequilibrium open system, to which a quantum mechanical reservoir theory successfully applies (*1–3*). An important class of light termed coherent states, which feature quantum mechanical zero-point fluctuations around its average field excitation, has also been extensively studied in the context of quantum optics (*4*). The ordinary shot noise usually observed on direct detection of the light has been attributed to zero-point fluctuations. It was generally accepted among physicists and quantum electronics engineers that an ideal laser pumped at well above the oscillation threshold generates a coherent state of light with the exception of random-walk phase diffusion noise (*5*). Various experimental facts, such as Poissonian photoelectron statistics, shot noise–limited photocurrent spectra, and Gaussian homodyne detection output statistics, supported the above conclusion. It was also suggested that the quantum statistical properties of a semiconductor laser are essentially the same as those of other optically pumped lasers (*6*). A semiconductor laser shown in Fig. 1 converts electrons injected via an electrical current to coherent photons by stimulated emission.

However, recent theoretical and experimental studies on quantum noise properties of a semiconductor laser have revealed that the semiconductor laser produces photon number squeezed states with photon number noise reduced to below the standard quantum limit (SQL) (*7–11*). The conventional quantum reservoir theory cannot be applied directly to a semiconductor laser because of the mutual coupling between the pump electrical circuit and the lasing junction. This generation scheme of photon number squeezed states is in sharp contrast to the conventional means of generating squeezed states of light (*12–15*), in which coherent states produced by a laser are unitarily transformed to squeezed states by various nonlinear optical processes (*16*).

This article reviews the theoretical and experimental aspects of the generation of photon number squeezed states in semiconductor lasers. Some related topics, such as the differences in optical partition noise and electrical partition noise and the quantum correlation between junction voltage noise and photon number noise, are also discussed. Future possibilities, which include squeezed vacuum-state generation in an injection-locked semiconductor laser and single photon-state generation at a repetition frequency $f = I/e$, where I is current and e is electronic charge, by correlated electron-hole pair radiative recombination (optical analog of Coulomb blockade), will be briefly addressed.

Photon Number Squeezed States in Pump Noise–Suppressed Lasers

The macroscopic coherence of light and matter in a laser is established by the balance between an ordering force of "systems" (gain saturation in the case of a laser) and fluctuating forces from external "reservoirs." The conventional quantum mechanical reservoir theory for a laser treats only three degrees of freedom as "systems": cavity internal field, population inversion, and dipole moment. All of the other degrees of freedom are considered as "reservoirs" and eliminated by use of the quantum mechanical fluctuation-dissipation theorem (*1–3*).

A fluctuating force pertinent to our discussion is that from an external pump source. The pump fluctuating force for optically pumped lasers is usually shot noise–limited, because the pump light

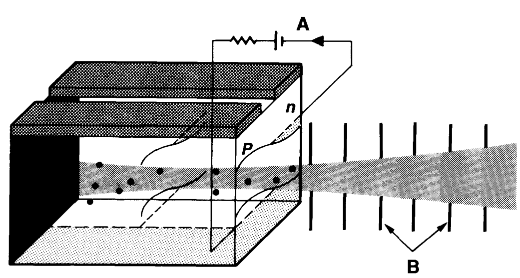


Fig. 1. Schematic of a typical injection current–pumped semiconductor laser. (**A**) A high-impedance, constant-current source, which injects electrons into the p-type active region at a constant rate. (**B**) An incident vacuum fluctuation, which is reflected back as a number-phase squeezed state from the laser.

Y. Yamamoto and S. Machida are at NTT Basic Research Laboratories, Musashinoshi, Tokyo 180, Japan. W. H. Richardson is at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

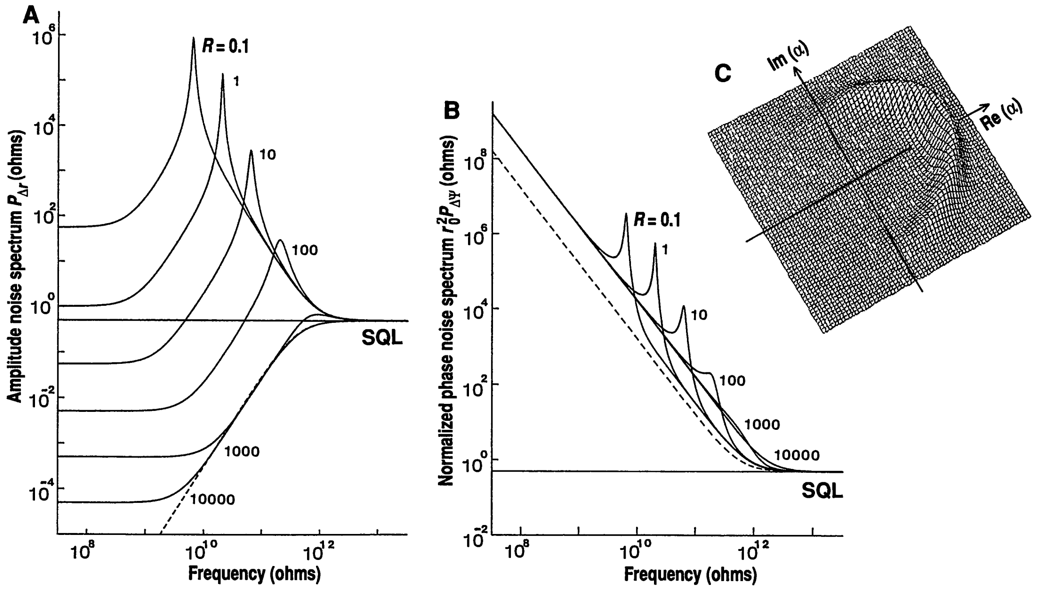


Fig. 2. (**A**) The amplitude (photon number) noise spectra normalized by the SQL of a pump noise–suppressed laser for various normalized pump rates $R \equiv P/P_{th} - 1$, where P_{th} represents threshold pump rate. (**B**) The normalized phase noise spectra for various normalized pump rates. The excess phase noise above the Schawlow-Townes phase diffusion limit shown by the dashed line is due to an anomalous dispersion effect (anomalous dispersion coefficient $\alpha = 2$). (**C**) The quasi-probability density of a number-phase minimum uncertainty state.

absorption by a gain medium is considered as a random Poisson point process. Of course, this is not a fundamental limit imposed by quantum mechanics. We may consider a thought experiment in which a gain medium is excited by photon number states of light with a perfect absorption efficiency. The pump fluctuating force determined by the photon number noise of pump light is reduced to zero for such a case (*17*). The phase noise of pump light does not contribute to the pump noise of a laser at all, because a laser oscillator is an incoherently pumped device in contrast to a parametric oscillator, which is a coherently pumped device (*18*).

The photon number and phase spectra for a pump noise–suppressed laser are shown in Fig. 2, A and B (*7*). The photon number noise is reduced to below SQL at frequencies below the cavity cutoff frequency at pump rates well above the threshold. The physical interpretation for the above result is rather straightforward. Every absorbed pump photon is emitted sooner or later as a coherent lasing photon from the cavity, in which the stimulated emission by a strong laser field is much stronger than a random spontaneous emission at high pump rates. Therefore, if the emitted photon number is counted for a measurement time interval longer than the population lifetime and the photon lifetime, the photon statistics of the laser output should be the same as the photon statistics of the pump light. A high conversion efficiency is indeed only one criterion for such preservation of the absorbed pump photon statistics to the emitted coherent photon statistics.

However, the phase noise is increased to above SQL at frequencies below the cavity cutoff frequency because of the so-called Schawlow-Townes phase diffusion process (*1–3*). The product of the reduced photon number spectrum $S_{\Delta N}(\Omega)$ and the increased phase spectrum $S_{\Delta\psi}(\Omega)$ satisfies the Heisenberg uncertainty principle,

$$S_{\Delta N}(\Omega) S_{\Delta\psi}(\Omega) \geq 1 \tag{1}$$

In the limit of high pump rates, the product is higher by only a factor of 2 over the minimum uncertainty product (*7*). A finite photon lifetime introduces the residual photon number noise $S_{\Delta N}(\Omega)$ by a stochastic photon output process and, at the same time, it stores coherent photons inside the cavity, which leads to the stabilization of the phase noise $S_{\Delta\psi}(\Omega)$ by a stimulated emission. This result suggests that the output field from a pump noise–suppressed laser is not far from the number-phase minimum uncertainty states shown in Fig. 2C (*19*). Similar states are also produced by either the quantum phase diffusion in a Kerr nonlinear medium (*20*) or the state reduction induced by a quantum nondemolition measurement (*21*) or quantum measurement of Pauli's first kind (*22*).

Constant Current–Driven Semiconductor Lasers

Several schemes have been proposed to suppress the pump fluctuating force of a laser. One scheme utilizes sub-Poissonian space-charge–limited electron beams to obtain the Franck-Hertz effect (*23*). Another utilizes three-level atoms as a gain medium, in which the pump process is self-regulated by a limited number of ground-state atoms (*24*). In the special case of a three-level laser system with equal population decay rates for upper and lower states, however, the photon statistics of the laser output are only partially sub-Poissonian (*25, 26*). The most practical and direct way of suppressing the pump fluctuating force is to use a constant-current source for the semiconductor injection laser.

The junction current noise of a *pn* diode driven by a constant-voltage source is shot noise–limited (*27*). This fact has been erroneously identified as a "shot noise–limited pump fluctuating force" for a semiconductor laser. The mistake in this argument is twofold. First, the junction current noise is not a pump fluctuating force (cause) but a relaxation current pulse (result) for the radiative recombination (photon emission) event in a junction (*8*). Second, a semiconductor laser usually operates under a constant-current mode rather than a constant-voltage mode (*8*).

The difference between constant-voltage mode and constant-current mode is schematically shown in Fig. 3. When a *pn* junction is driven by a constant-voltage source with a source resistance R_S much smaller than the diode's differential resistance R, that is, $R_S << R = k_B T/eI$, where k_B is the Boltzmann constant and T is temperature, the junction voltage drop resulting from the radiative recombination of an electron-hole pair is quickly eliminated by an external circuit relaxation current pulse. By the time the next radiative recombination event occurs, the junction voltage (number of electron-hole pairs in a junction) has recovered to the original value. In such a memoryless system, photon emission events follow a Poisson point process and the junction current carries full shot noise. On the other hand, when a *pn* junction is driven by a constant-current source with a source resistance much larger than the diode's differential resistance, that is, $R_S >> R$, the junction voltage is not pinned by a source but is free to fluctuate. The fluctuation in the junction voltage caused by the radiative recombination is not recovered at the time of the next radiative recombination event. In such a system with memory, the photon emission events follow a sub-Poissonian process and the junction current carries noise below the shot noise level because of self-stabilization.

The pump fluctuating force of a semiconductor laser is identified as the thermal noise generated in the source resistance R_S whose spectral density is $4k_BT/R_S$ (*7, 8*). The thermal noise is much higher than the shot noise value $2eI$ for a constant-voltage source with $R_S << R$ but is much smaller than the shot noise value for a constant-current source with $R_S >> R$. The thermal noise–limited pump fluctuating force and the dissipation rate of the junction voltage through the pump circuit satisfy the fluctuation-dissipation theorem exactly (*28*). In the case of a constant-current source, the dissipation rate $(CR_s)^{-1}$ of the junction voltage through a pump circuit is very slow and the fluctuating force from the pump circuit $4k_BT/R_S$ is also small. The two conditions necessary for the generation of photon number squeezed states in semiconductor lasers, that is, the free voltage fluctuation and the pump noise suppression, are satisfied simultaneously by $R_S >> R$.

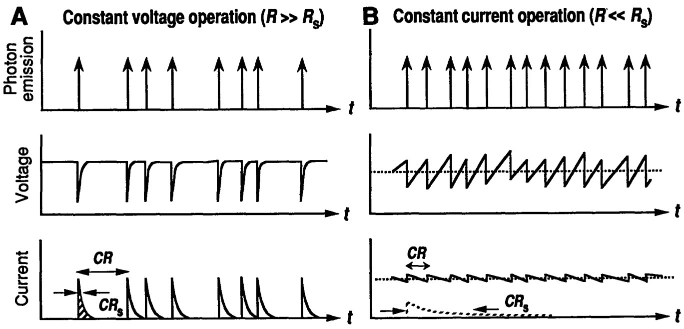


Fig. 3. The junction voltage fluctuation and the relaxation current pulse caused by a photon emission event for (**A**) $R >> R_S$ (constant-voltage driving case) and (**B**) $R << R_S$ (constant-current driving case). C is the diffusion capacitance of a *pn* junction. The time constant CR corresponds to the electron lifetime, and CR_s is the external circuit relaxation time constant.

There is an analogy between the quantum states established in a *pn* junction laser and in a superconductor tunnel junction. A Bloch oscillation at a frequency $f = I/2e$ is achieved in an ultrasmall superconductor tunnel junction driven by a constant-current source I, in which the number of tunneled electron pairs is regulated but the relative phase of the two superconductors is randomized (*29*). This is similar to the present scheme for the generation of photon number squeezed states in a *pn* junction laser driven by a constant-current source. On the other hand, an ordinary Josephson oscillation at a frequency $f = 2eV/h$ (h is Planck's constant) is observed in a macroscopic superconductor tunnel junction driven by a constant-voltage source V, in which the relative phase of the two superconductors is fixed, but the number of tunneled electron pairs is random (*29*). This is similar to coherent state generation in a conventional laser oscillator.

Squeezed State Generation Experiments

Figure 4A shows a dual-balanced detector setup for measuring the photon number noise spectrum from a semiconductor laser (*30*). A semiconductor laser output is split equally into the two arms by a half-wave plate and polarization beam splitter. One detector output current I_1 is delayed by a coaxial cable and combined with the other undelayed detector output current I_2 by a differential amplifier or 180° hybrid. For a fluctuation frequency Ω_{in} satisfying $\Omega_{in}\tau = 2N\pi$, where τ is the delay time and N is an integer, the differential amplifier output, $I_1 - I_2$, calibrates the shot noise value. For a fluctuation frequency Ω_{out} satisfying $\Omega_{out}\tau = (2N + 1)\pi$, the differential amplifier output $I_1 + I_2$ measures the photon number noise of the laser output. Thus, the differential amplifier output simultaneously displays the laser noise and corresponding shot noise values with a frequency period of $\Delta\Omega = 2\pi/\tau$ on a spectrum analyzer.

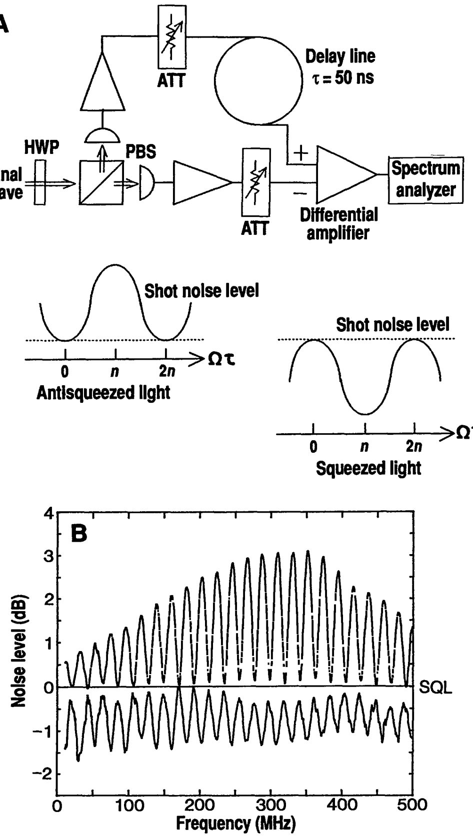


Fig. 4. (**A**) A dual-balanced-detector setup for measuring the intensity noise of a semiconductor laser: HWP, half-wave plate; PBS, polarization beam splitter; ATT, attenuator and equalizer. (**B**) The measured intensity noise spectra normalized by the shot noise value for two pump rates, $I/I_{th} = 1.03$ (upper curve) and $I/I_{th} = 13.6$ (lower curve).

The measured noise spectra at two different pump rates for a GaAs transverse junction stripe semiconductor laser are shown in Fig. 4B (*30*). The noise spectra are normalized by the shot noise value, which is independently calibrated by a light-emitting diode with the same wavelength as the laser. The noise spectrum at the pump rate just above the threshold, $I/I_{th} = 1.03$, shows a lower noise value at Ω_{in} and a higher noise value at Ω_{out}, where I_{th} is the threshold current. This is a characteristic of antisqueezed (super-Poissonian) light. The noise spectrum at the pump rate well above the threshold, $I/I_{th} = 13.6$, shows a higher noise value at Ω_{in} and a lower noise value at Ω_{out}, which is a characteristic of squeezed (sub-Poissonian) light.

The degree of squeezing is degraded by the Poissonian partition noise associated with optical loss. To increase the light collection efficiency, a GaAs transverse junction stripe laser, with less than 3% front facet reflectivity R_1 and more than 90% rear facet reflectivity R_2, is operated at 66 K to minimize the free carrier absorption loss and is directly coupled to an Si photodetector to minimize the coupling loss. Figure 5A shows theoretical and experimental photon number noise values normalized by the shot noise value versus the normalized pump rate $I/I_{th} - 1$ (*30*). The experimental results are corrected for a detection quantum efficiency of about 89%, so the degree of squeezing shown in Fig. 5 corresponds to that of the laser output. The experimental maximum degree of squeezing, −14 dB

($\simeq$0.04), is in reasonable agreement with the theoretical limit imposed by the output coupling efficiency

$$\eta = \frac{\ln\left(\dfrac{1}{R_1}\right)}{\ln\left(\dfrac{1}{R_1 R_2}\right)} \simeq 0.97 \tag{2}$$

of the laser.

Poissonian Optical Partition Noise Versus Sub-Poissonian Electrical Partition Noise

The overall quantum efficiency [(detector current)/(laser current)] in the above experiment was only 48% (*31*). If all loss processes could commonly introduce a Poissonian partition noise, squeezing of more than 3 dB would be impossible. An explanation of the counterintuitive experimental result has been worked out (*31, 32*). The GaAs laser used in the experiment has a nonlasing junction in parallel with the lasing junction (Fig. 5B). Under the operating conditions of $T \simeq 66$ K and $I \simeq 30$ mA, the leakage current is estimated to be approximately equal to the current injected into the lasing junction (*33*). That is, the overall quantum efficiency is degraded mainly by current division. This current division introduces a new noise source, which serves as a pump fluctuating force for the lasing junction.

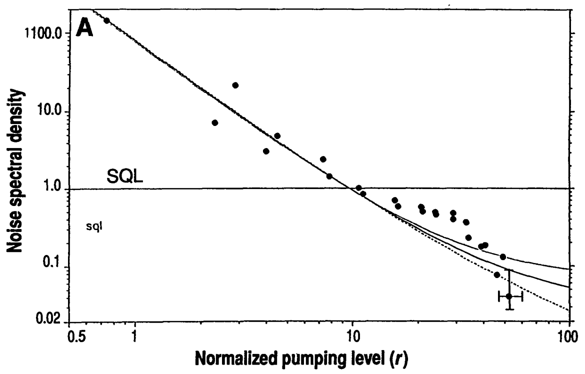
A unified circuit theory has been developed for treating optical partition noise and electrical partition noise in the same circuit language (*32*). The current noise in two branching arms driven by a constant-current source is given by

$$i_1 = -i_2 = \frac{v_2 + v_{d2} - v_1 - v_{d1}}{2(R + R_d)} \tag{3}$$

where it is assumed for simplicity that the two series resistances connected to the two (lasing and nonlasing) junctions are equal, $R_1 = R_2 = R$, and that the differential resistances of the two junctions are also equal, $R_{d1} = R_{d2} = R_d$. Here, v_i and v_{di} are the noise voltages associated with R and R_d. The spectra of i_1 and i_2 are given by

$$S_{i_1} = S_{i_2} = \begin{cases} \dfrac{2k_B T}{R} (R >> R_d) \\ \dfrac{1}{2} eI (R << R_d) \end{cases} \tag{4}$$

Here the quantum zero-point fluctuation, $2\hbar\Omega R$, associated with R is neglected because it is much smaller than the thermal noise, $4k_B TR$. Thus, if $R << R_d$, the current noise is only -3 dB below the shot noise value. That is, current division introduces a Poissonian electrical partition noise. On the other hand, if $R >> R_d$, the current noise is much smaller than the shot noise value. This condition is satisfied at a high current level $I >> 2k_B T/eR$ for any small series resistance R. In this way, the sub-Poissonian character of a constant-current source is preserved against current division. The theoretical curve in Fig. 5A assumes a series resistance $R = 50$ ohms. In the case of photon flux division, the quantum zero-point fluctuation, $2\hbar\Omega R$, is much larger than the thermal noise, $4k_B TR$, for which a Poissonian partition noise is always associated (*31*). Although such a macroscopic (circuit) theory successfully explains the experimental results, a microscopic theory, that is, a quantum theory for transport and division of charged particles in conducting wires, has yet to be worked out (*33*).



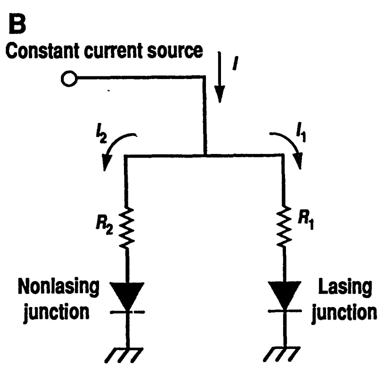


Fig. 5. (**A**) The theoretical (lines) and experimental (●) intensity noise values normalized by the shot noise value versus the normalized pump rate $R \equiv I/I_{th} - 1$. The experimental results are corrected for a detection quantum efficiency of 89%. (**B**) A model for current division into a lasing junction and a nonlasing junction.

Quantum Correlation Between Photon Number and Junction Voltage

The product of the reduced photon number noise and the increased phase noise is generally higher than the minimum uncertainty product, $S_{\Delta N}(\Omega) S_{\Delta\phi}(\Omega) = 1$, as shown in Fig. 2. The increased phase noise due to a random-walk phase diffusion is a noise inherent in any negative conductance oscillators that do not have a restoring force for phase. On the other hand, it is possible that there is a hidden measurement for photon number in semiconductor lasers, which could lead to a further reduction in photon number noise to the minimum value required by the uncertainty product.

In a constant current–driven semiconductor laser, the junction voltage fluctuation is related to the electron number fluctuation through a junction capacitance. The electron number fluctuation and the photon number fluctuation are negatively correlated through the spontaneous emission, stimulated emission, and absorption. Consequently, it is expected that the photon number noise can be determined by measuring the junction voltage noise.

An experimental setup for measuring the quantum correlation between photon number noise and junction voltage noise is shown in Fig. 6A (*34*). The photon number noise of a semiconductor laser is measured by detector D2, and the shot noise value is calibrated by a light-emitting diode and detector D1. The junction voltage noise is measured independently and combined with the delayed photon number noise by a wideband 180° hybrid. Figure 6B shows the measured junction voltage noise (trace a), laser intensity noise (trace b), shot noise (trace c), and combined noise of junction voltage and laser intensity (trace d) (*35*). The sinusoidal variation shown by trace d manifests the correlation between the photon number noise and the junction voltage noise. In the absence of the correlation, trace d would be flat and the noise power numerically equal to the sum of the two noise powers given by traces a and b. The squeezed intensity noise is further reduced by the addition of the junction voltage noise, which indicates that the correlation is negative and penetrates into a quantum region.

The junction voltage can be used as a quantum measurement probe of the photon number. Conditioned on the junction voltage measurement result, the photon number noise can be reduced to near the minimum value dictated by the uncertainty principle (*36*). This fact can be interpreted from the viewpoint of a "quantum watchdog effect" (*37*). That is, the photon number is always monitored by the external pump circuit (the watchdog), even though an experimentalist does not actually read out the junction voltage. Partial (or perfect) reduction of a wave packet continuously occurs irrespective of readout actions made by the experimentalist. Such a hidden measurement introduces back-action noise on the conjugate observable of the measured observable. This inevitable back-action noise emerges as Schawlow-Townes phase diffusion noise caused by the dephasing of dipole moments, that is, random phase spontaneous emission (*36*).

Future Possibilities

Photon number squeezed states cannot be used to improve interferometric phase measurements such as a gravitational wave detection laser interferometer and a laser gyroscope. Such measurements require a reduced phase noise rather than a reduced photon number noise, or more generally they require squeezed vacuum states (*38*). It is possible to change photon number squeezed states into squeezed vacuum states by the setup shown in Fig. 7 (*39*). A constant current–driven semiconductor laser, denoted as a slave laser in Fig. 7, is injection-locked by an external master laser oscillator. The phase correlation between the squeezed slave laser output and the master laser output is established without sacrificing appreciably the degree of photon number squeezing (*40*). The classical signal part of the squeezed output from the slave laser can be canceled interferometrically; here, the quantum noise of the master laser output can be suppressed with the use of a high-transmission mirror (*39*). Because a semiconductor laser emission wavelength can be chosen at any wavelength region from 0.45 to 1.7 μm, this squeezed vacuum-state generation technique can be applied to any laser interferometer system.

As shown in Fig. 2, photon number squeezed states can be generated only at pump rates well above the threshold, because constantly injected electron-hole pairs are spontaneously emitted mainly into nonlasing modes at pump rates below and near the threshold. Random deletion due to such spontaneous emission introduces a Poissonian partition noise, which is even amplified at pump rates near the threshold. However, it is possible to confine all spontaneous emission into a single lasing mode by using a cavity quantum electrodynamic technique (*41*). The photon number spectra for such a microcavity semiconductor laser with a unity coupling efficiency of spontaneous emission are reduced to below SQL at any pump rate (Fig. 8) (*42*). Only one criterion for generating photon number squeezed states in a constant current–driven semiconductor laser, a high conversion efficiency from electrons to photons, is satisfied by the microcavity without requiring the stimulated emission. Low-intensity squeezed light generated by such a light-emitting diode may find applications to the optical interconnection inside a large-scale integrated circuit, in which the energy dissipation for communication is already much larger than that for signal processing.

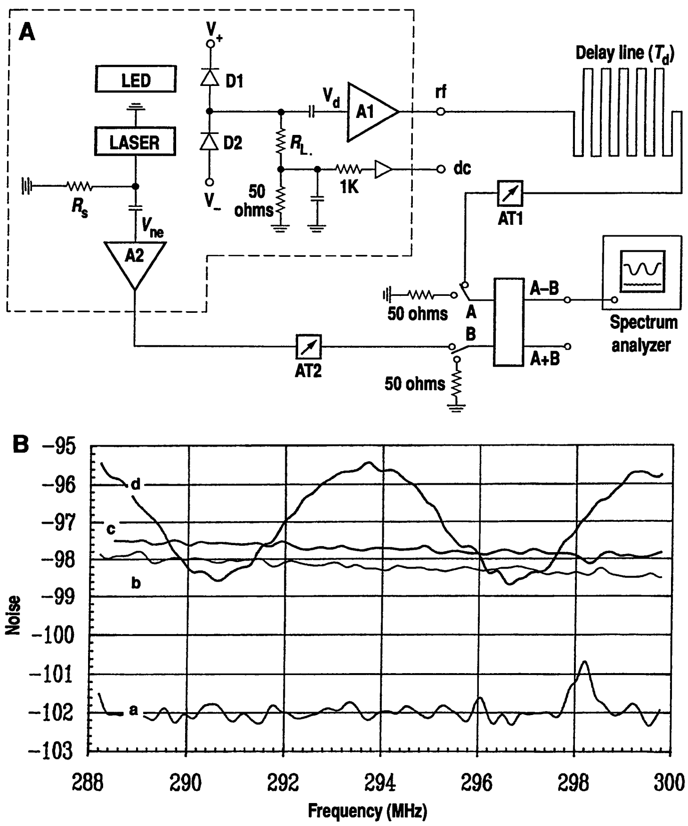


Fig. 6. (**A**) An experimental setup for measuring the quantum correlation between the photon number noise and the junction voltage noise; LED, light-emitting diode. (**B**) The measured junction voltage noise (trace a), laser intensity noise (trace b), shot noise produced by a light-emitting diode (trace c), and combined noise of junction voltage and laser intensity (trace d). The ordinate is the noise power P_n expressed as (dB_m) ≡ 10 $\log_{10} P_n$ (nW). A1, A2: amplifiers. AT1, AT2: attenuators.

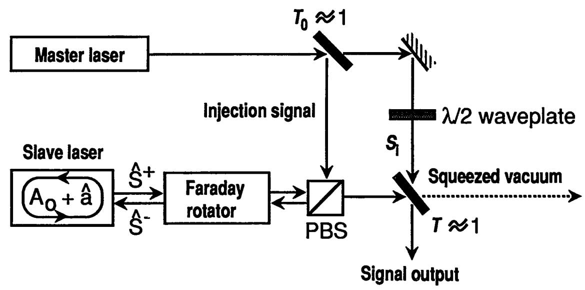


Fig. 7. An injection-locked semiconductor laser for generating squeezed vacuum states. A_0 = slave laser internal field; $\hat{a}$ = internal field fluctuation; S^- = injection field; S^+ = slave laser output field; S_i = master laser field; PBS = polarization beam splitter.

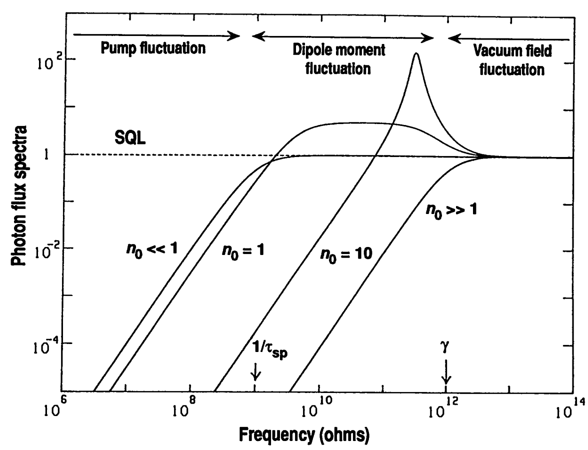


Fig. 8. The photon number spectra normalized by SQL of a microcavity semiconductor laser for various average photon number n_0. n_0 = 1 corresponds to the laser oscillation threshold. It is assumed that the coupling efficiency of spontaneous emission into a single lasing mode is unity.

If we can decrease the current level I to less than e/τ_{sp} and satisfy the constant-current operation condition, where τ_{sp} is the spontaneous emission lifetime, the charging time for one electron-hole pair into a junction can become longer than the radiative recombination lifetime. In such a case, coexistence of continuous uniform charging into the junction and discrete radiative recombination of an electron-hole pair will achieve the junction voltage oscillation and single photon emission at a frequency of $f = I/e$ (*43*). This is an optical analog of Coulomb blockade, or single-electron (electron-pair) tunneling oscillation in an ultrasmall capacitance tunnel junction (*29*). It is expected to open up a new field of combined single electronics and single photonics.

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44. Support for W.H.R. on part of the work was provided by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Iraq and the Future of Nuclear Nonproliferation: The Roles of Inspections and Treaties

JOSEPH F. PILAT

In the aftermath of the Gulf War, revelations about Iraq's extensive program to develop nuclear weapons challenge the future of the international nuclear nonproliferation regime. Until inspections sanctioned by the U.N. Security Council began, Iraq's violations of its obligations under the Treaty on the Nonproliferation of Nuclear Weapons and its related safeguards agreement with the International Atomic Energy Agency went undetected. The ultimate impact of Iraq's behavior on the regime cannot yet be determined, but there is now an opportunity to improve safeguards and other aspects of the regime, including strengthening export controls and proliferation intelligence collection and sharing and the development of appropriate response capabilities.

SINCE ITS ENTRY INTO FORCE IN 1970, THE TREATY ON THE Nonproliferation of Nuclear Weapons (NPT) has been the centerpiece of the international nuclear nonproliferation regime. With more than 140 parties, it is the most widely adhered to arms control treaty in history. As recently as the Fourth Review Conference of NPT Parties (Geneva, 1990), there was a consensus on the value of the treaty, although there was no formal declaration of that consensus. Now, what was long assumed to be of enduring value has come under question because of the pursuit by Iraq, an NPT party, of an ambitious nuclear weapon program.

Before assessing the regime implications of recent developments in Iraq, it is useful to review provisions of the NPT. The main objective of the treaty is to prevent the spread of nuclear weapons to

The author is at the Center for National Security Studies, Los Alamos National Laboratory, Los Alamos, NM 87545.