Photon-number-squeezed recombination radiation in semiconductors

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Received February 10, 1987; accepted April 10, 1987

Recombination radiation from semiconductors can exhibit a squeezed photon number by use of a specially designed space-charge-limited light-emitting structure. The light will exhibit a small Fano factor and large photon flux. The structure will be small in size and have the capability of being modulated at a high rate.

We recently reported the generation of cw photon-number-squeezed (sub-Poisson) light from a Franck–Hertz experiment in which Hg vapor was excited by inelastic collisions with a space-charge-limited (quiet) electron beam.[1] The experiment operates by transferring the anticlustering properties of the electrons, resulting from Coulomb repulsion, to the photons. The direction of transfer is the inverse of that encountered in the usual photodetection process, in which the statistical character of the photons is imparted to the photoelectrons. Since the mechanism involves ordinary spontaneous emission, it is a first-order optical process and can be expected to produce a strong effect.[2]

It has been shown that the combination of sub-Poisson excitations, each associated with a single-photon emission, leads to sub-Poisson photon counts, provided that certain conditions on the characteristic times and areas of the detection process are obeyed.[2] The sub-Poisson electron excitations are characterized by a time constant τ_e that represents the time over which excitation events are anticorrelated (antibunched). The single-photon emissions, on the other hand, are characterized by a photon excitation/emission lifetime τ_p. The detected light will be sub-Poisson, provided that $T \gg \tau_e, \tau_p$ and $A \gg A_c$, where T is the detector counting time, A is the detector counting area, and A_c is the coherence area.

In spite of these conditions being satisfied in the Franck–Hertz experiment, the light was only weakly sub-Poisson, principally because of optical losses in the experimental apparatus.[3] A useful source of such light should exhibit a photon Fano factor $F_n(T)$ that is substantially less than unity and should produce a large photon flux [corresponding to a large average photon number $\langle n(T) \rangle$]. If the light is to be used in an application such as light-wave communications, the switching time (or symbol duration) T should also be able to be made small so that the device can be modulated at a high rate.[4] On the other hand, T must be sufficiently large in comparison with the characteristic times τ_e and τ_p to ensure that the sub-Poisson character of the photons is captured in the counting time.[1,2] Ideally, the device should also be small in size and produce a directed output so that the light can be coupled to an optical fiber. The structure should be designed in such a way that light loss is minimized.[3]

A number of suggestions have been made for achieving sub-Poisson excitations and single-photon emissions. Probably the simplest method is to discharge a capacitor C, containing a fixed charge, through a circuit containing a photon emitter such as a light-emitting diode (LED). The current waveform will then be a nonstationary pulse with time constant $\tau = RC$ (where R is the resistance of the circuit). A steady-state version of this experiment would make use of a fixed current stabilized by an *external* feedback circuit to drive the LED. This can be achieved by means of a constant-voltage source in series with an external resistor,[5] R, or in series with some other optoelectronic component with a suitable I-V characteristic. Other configurations, in which the anticorrelation property of the electrons is achieved by using external feedback, have been suggested.[5,6]

However, in all cases using external feedback, the characteristic anticorrelation time of the excitations τ_e is determined by the feedback time constant of the loop τ_f. A lower limit on the feedback time constant is imposed by the response time and transit time of carriers through the device and by the RC characteristics of the feedback circuitry. In general, an internal feedback process, such as space charge, will provide a more effective means of providing sub-Poisson excitations than will external feedback. This is because an internal physical process is likely to result in a smaller value of τ_e than will external electronic circuitry. Configurations

0740-3224/87/101663-05$02.00

making use of space-charge-limited excitations will therefore have the capacity of being switched faster[7] than those making use of external feedback.

Using another approach altogether, it has been suggested that sub-Poisson light can be generated by the use of *nonlinear-optics* schemes that rely on correlated photon pairs and selective deletion.[8,9] An experiment using parametric downconversion[10,11] and dead-time optical gating has indeed been successfully used to generate such light.[12] Unfortunately this new source of sub-Poisson light suffers from a number of familiar problems: a Fano factor very close to unity, low photon flux, and slow switching speed.

It can be shown that the sub-Poisson electron-excitation methods are, in general, superior to the nonlinear-optics methods. The advantage stems from several factors: (1) Photons naturally gravitate toward Poisson counting statistics and shot-noise fluctuations.[2,3] It is difficult for the nonlinear-optics methods to undo this natural Poisson photon noise. Electrons, on the other hand, are often governed by quieter thermal-noise fluctuations,[7,13] thereby permitting $F_n(T)$ to be made smaller. (2) Nonlinear-optics schemes in which Poisson photons are first generated (subject to a source power constraint) and subsequently converted into sub-Poisson photons cannot provide performance gain in applications such as light-wave communications.[4] (3) Sub-Poisson electron-excitation configurations produce light by means of efficient single-photon transitions; large values for the photon flux are therefore easily achieved. Nonlinear-optics methods, on the other hand, rely on (relatively) inefficient multiple-photon transitions. Furthermore, they are subject to photon interference effects that can limit the degeneracy parameter (and therefore the photon flux) to small values.[8] (4) Electron excitations, especially those mediated by a physical process such as space charge, can attain a small characteristic response time τ_e so that fast switching can be achieved.[7] (However, as a point of interest, it should be noted that correlated photon pairs and postdetection processing, such as subtraction and correlation, may be useful in specialized applications.[14])

We conclude that an ideal source of squeezed-photon-number light will operate by means of sub-Poisson excitations, mediated by an internal physical feedback process, and will incorporate a mechanism for achieving highly efficient single-photon emissions. It should be small in size and preferably be able to produce light in a directed beam.

We are therefore led to propose a semiconductor device structure in which sub-Poisson electron excitations are attained through space-charge-limited current flow and single-photon emissions are achieved by means of recombination radiation. A device of this nature will emit photon-number-squeezed recombination radiation. The energy-band diagram for such a space-charge-limited light-emitting device (SCLLED) is illustrated in Fig. 1. Sub-Poisson electrons are directly converted into sub-Poisson photons, as in the space-charge-limited Franck–Hertz experiment,[1] but these are now recombination photons in a semiconductor. In designing such a device, carrier and photon confinement should be optimized and optical losses should be minimized.

The basic structure of the device is that of a p^+–i–n^+ diode. As an example, the p^+ region may consist of $Al_{0.35}Ga_{0.65}As$, several thousand angstroms thick and doped to $p^+ \approx 5 \times 10^{17}\ cm^{-3}$, and of a layer of smaller-gap material

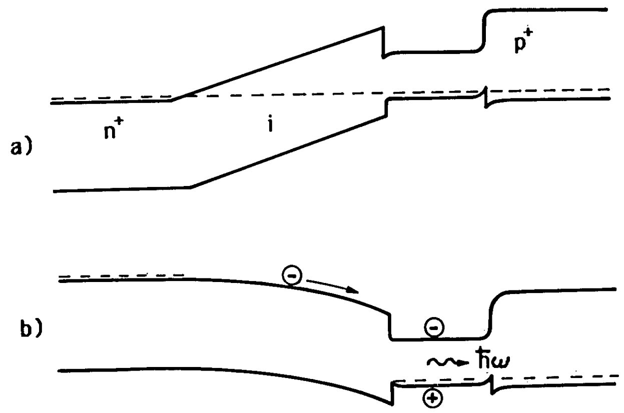

Fig. 1. Energy-band diagram of a space-charge-limited light-emitting device under (a) equilibrium conditions and (b) strong forward-bias conditions. The curvature of the intrinsic region under forward-bias conditions indicates the space-charge potential. E_F is the Fermi level, and $\hbar\omega$ is the photon energy.

for confinement, of GaAs with the same thickness and doping level. The intrinsic (i) region would consist of a 2–10-μm layer of ultralow-doped (nearly intrinsic) $Al_{0.35}Ga_{0.65}As$. The n^+ region would also be of $Al_{0.35}Ga_{0.65}As$. The structure should be grown on a conductive substrate. A 0.15-eV discontinuity in the valence band, between the GaAs and the $Al_{0.35}Ga_{0.65}As$ layers of the p^+ region, would ensure hole confinement in the low-gap material at room temperature. The conduction-band discontinuity should be about 0.25 eV. Near-infrared recombination radiation would be emitted from the GaAs layer in this LED-like region. This structure is appropriate for a waveguiding edge-emitting geometry. To maximize the external quantum efficiency, a surface-emitting geometry may be preferable; the surface should be dome shaped to eliminate total internal reflection. In this case the p^+ AlGaAs layer is not necessary.

The I-V characteristic for a single-carrier conventional space-charge-limited diode is given by the approximate relationship[15]

$$\langle I_e\rangle \approx (9/8)(\epsilon_s\mu_n/L^3)A\langle V_e\rangle^2, \tag{1}$$

where $\langle I_e\rangle$ is the average forward current, ϵ_s is the permittivity of the medium, μ_n is the electron mobility, $\langle V_e\rangle$ is the applied forward-bias voltage, and A is the device area. This expression is valid under strong injection conditions (applied bias voltage > built-in potential), provided that $L \gg L_D$, where L is the thickness of the intrinsic region and L_D is the electron diffusion length. Typical parameter values for the structure shown in Fig. 1 are $\epsilon_s \approx 1.15 \times 10^{-12}$ F/cm, $\mu_n \approx 1000\ cm^2/V$ sec, $L \approx 2.5\ \mu m$, $A \approx 10^{-4}\ cm^2$, $\langle V_e\rangle \approx 2$ V, and $\langle I_e\rangle \approx 33$ mA.

The current noise in such devices can be quite low. It has a thermal (rather than shot-noise) character.[13,16] The current-noise spectral density $S_e(\omega)$ for a device in which only electrons participate in the conduction process takes the simple form[16]

$$S_e(\omega) = 8k\theta \mathrm{d}\langle I_e\rangle/\mathrm{d}\langle V_e\rangle, \tag{2}$$

where k is Boltzmann's constant, θ is the device temperature in degrees Kelvin, $\mathrm{d}\langle I_e\rangle/\mathrm{d}\langle V_e\rangle$ is the differential conductance of the device, and ω is the circular frequency. Combining expression (1) and its derivative with Eq. (2) provides

$$S_e(\omega)/2e\langle I_e\rangle = 8k\theta/e\langle V_e\rangle, \quad (3)$$

where e is the electronic charge. By definition, the electron current is sub-shot noise, provided that

$$S_e(\omega)/2e\langle I_e\rangle = 8k\theta/e\langle V_e\rangle < 1. \quad (4)$$

The statistical properties of light generated by sub-Poisson electron excitations and single-photon emissions are well understood.[2] Light is considered to be sub-Poisson when the photon Fano factor $F_n(T)$ is less than unity,[17] i.e., when

$$F_n(T) = \mathrm{var}[n(T)]/\langle n(T)\rangle < 1. \quad (5)$$

The quantities $\mathrm{var}[n(T)]$ and $\langle n(T)\rangle$ are the photon-number variance and photon-number mean in the counting time interval $[0, T]$, respectively. A source of light may be sub-Poisson for one value of T and super-Poisson for another value of T. In the limit of a long-counting-time/large-area detector, the photons behave as classical particles, and the expected *photoelectron* (postdetection) Fano factor $F_m(T)$ is given by[1–3]

$$[F_m(T) - 1] = \eta\beta[F_e(T) - 1], \qquad T \gg \tau_e, \tau_p; A \gg A_c. \quad (6)$$

Here $F_e(T)$ is the Fano factor of the exciting electron stream and η is the overall quantum efficiency from electrons to detected photons. The quantity β accounts for the admixture of independent Poisson background light ($0 \le \beta \le 1$; $\beta = 1$ in the absence of such background light).[3]

The analog versions of Eqs. (5) and (6) are of interest when the detected photocurrent or the excitation current is continuous (as expected for the SCLLED) rather than when they are a sequence of discrete events. The formula analogous to Eq. (6) relates the power spectral densities of the excitation current $S_e(\omega)$ and the detected photocurrent $S_m(\omega)$. The ratios $S_j(\omega)/2e\langle I_j\rangle$ may be regarded as Fano factors $F_j(T_j)$, where $j = e$, m and the $\langle I_j\rangle$ are the mean values of the respective currents. Here the counting times T_j play the role of inverse bandwidths of the filters involved. In the limits $T_j \gg \tau_e, \tau_p$ and for $\omega \ll 1/\tau_e, 1/\tau_p$, we obtain

$$[S_m(\omega)/2e\langle I_m\rangle - 1] = \eta\beta[S_e(\omega)/2e\langle I_e\rangle - 1], \qquad \omega \ll 1/\tau_e, 1/\tau_p; \quad A \gg A_c. \quad (7)$$

It follows from Eqs. (4) and (7) that a sub-shot-noise electron-excitation current will always lead to a sub-shot-noise detected photon current. In accordance with Eq. (4), this implies sub-Poisson photon behavior when $8k\theta/e\langle V_e\rangle < 1$. For a space-charge-limited diode such as that shown in Fig. 1, it is estimated that $8k\theta/e\langle V_e\rangle \approx 0.1$ when $\theta = 300$ K and $\langle V_e\rangle = 2$ V. Further reduction of this ratio can be achieved by reducing the temperature of the device. It is interesting to note that, in the regime in which formulas (1) and (2) are valid, the degree of sub-shot-noise behavior is independent of the parameters ϵ_s, μ_n, L, and A. The values of these parameters do play a role in determining the photon flux and the device speed, however. More general results are available for the double-carrier space-charge-limited device.[13]

Using Eqs. (6) and (7), the degree of photon-number squeezing in the detected photons is then

$$F_m(T) = 1 + \eta(8k\theta/e\langle V_e\rangle - 1), \quad (8)$$

provided that background light is absent ($\beta = 1$). The overall quantum efficiency η is given by the product $\eta_{ext}\eta_d$, where η_{ext} is the external quantum efficiency of the SCLLED (the product of the internal quantum efficiency and the geometrical collection efficiency) and η_d is the external quantum efficiency of the photodetector. Although the internal quantum efficiency of a LED is $\gtrsim 0.5$,[18] the external quantum efficiency of a dome-shaped surface emitter is typically limited to about 0.15.[19,20] If a Si p–i–n photodetector is used to detect the photon-number-squeezed recombination radiation, we can take $\eta_d \approx 0.75$, whereupon $\eta \approx 0.1125$. Finally, assuming that $8k\theta/e\langle V_e\rangle \approx 0.1$, as determined above, we arrive at an overall estimated postdetection Fano factor $F_m(T) \approx 0.899$. A commercially available LED, with $\eta_{ext} \approx 0.03$, will yield $F_m(T) \approx 0.973$. In both cases, T can be as short as ≈ 1 nsec.

The SCLLED therefore promises to provide a source of photon-number-squeezed light with properties that are significantly superior to those of the Hg-vapor space-charge-limited Franck–Hertz source[1] [$F_m(T) \approx 0.998$ with $T \approx 1$ μsec] or the dead-time-gated parametric downconversion source[12] [$F_m(T) \approx 0.9998$, with $T \approx 19$ μsec]. Indeed, the degree of photon-number squeezing of recombination radiation from the SCLLED is essentially limited only by the geometrical collection efficiency.

The waveguide geometry and superfluoresence properties (single-pass stimulated emission) of the edge-emitting LED could be advantageous for providing improved beam directionality, switching speed, spectral properties, and coupling to an optical fiber.

The question arises about whether there might be a further advantage in combining space-charge-limited current injection with a semiconductor-laser structure rather than with the LED structure considered above. This could provide increased emission efficiency and additional improvement in the parameters discussed above. This will be beneficial when the laser can be drawn into a realm of operation in which it produces a state more akin to a number state[21] than a coherent state (the coherent state has Poisson photon-number fluctuations and minimal phase fluctuations). Machita *et al.*[5,22] have shown that this mode of operation can be attained in a semiconductor-laser oscillator, within the cavity bandwidth and at high-photon-flux levels, if the pump fluctuations are suppressed below the shot-noise level. Similar suggestions have been made by Smirnov and Troshin[23] and by Carroll.[14]

In summary, we have shown that the generation of sub-Poisson light is most readily achieved by the use of sub-Poisson electron excitations, mediated by a physical mechanism such as space charge, and single-photon emissions. We have proposed a space-charge-limited light-emitting structure as a fast and compact solid-state device that operates in this manner.

ACKNOWLEDGMENTS

This research was supported in part by the Joint Services Electronics Program and by the National Science Foundation through the Center for Telecommunications Research at Columbia University.

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