Conversion of Poisson Photons into Sub-Poisson Photons by the Action of Electron Feedback

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Poisson photons may be converted into sub-Poisson (amplitude-squeezed) photons by the action of an electron current configured in an external feedback loop. The generation mechanism involves single-photon transitions so that the source can be made arbitrarily sub-Poissonian. Nonlinear optics is not invoked. A useful configuration involves a photon emitter illuminating a detector-source combination in a closed-loop system. Two solid-state implementations of the detector-source combination are suggested.

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It is by now well known that nonclassical light can be generated in the laboratory. Such light may exhibit a variety of exotic properties including sub-Poisson photon statistics,[1,2] antibunching[3] (sub-Poisson photon statistics and antibunching need not necessarily accompany each other[4]), and squeezing.[5] Sub-Poisson light is also called amplitude-squeezed light.

The use of an external feedback system[6] for the generation of sub-Poisson light was first suggested by experiments in which feedback was used to produce sub-Poisson *electrons*.[7–9] Both the experiment of Walker and Jakeman[8] and the experiment of Machida and Yamamoto[9] involved laser (Poisson) photons illuminating a photodetector and an electronic negative feedback path from the detector to the source. In the former experiment the feedback directly controlled the photons at the output of the laser, whereas in the latter experiment the feedback controlled the current at the input to the laser. Nevertheless, the principle involved in the two experiments is the same.[6] Unfortunately, these simple configurations could not generate usable sub-Poisson *photons* since the feedback current is generated from the annihilation of the in-loop photons. However, under special circumstances an external feedback system can be used to produce sub-Poisson photons, such as when correlated photon pairs are available[10–12] or a quantum nondemolition measurement may be made.[13] The resultant light may only be weakly sub-Poissonian in such cases because these multiphoton processes involve a series of detections and/or a weak nonlinear effect.

In this Letter we propose a new approach for the conversion of Poisson photons into sub-Poisson photons *via single-photon transitions.* There does not appear to be any fundamental limit that would impede the technique from being used to produce an arbitrarily intense cw light source that is also arbitrarily sub-Poissonian. It makes use of the action of an electron current configured in a feedback loop. Consider, for example, an optical system in which a photon emitter illuminates a detector-source combination, in a closed-loop circuit. Two alternative configurations are shown in Fig. 1. The character of the photon emitter is immaterial; we have chosen it to be a light-emitting diode (LED) for simplicity, but it could be a laser.[6] In Fig. 1(a) the photocurrent derived from the detection of light from the LED photon emitter is negatively fed back to the LED input. It has been established both theoretically[6] and experimentally[9] that, in the absence of the block labeled "source," sub-Poisson electrons will flow in a circuit such as this. This conclusion is also generally valid in the presence of this block, which simply acts as an added impedance to the electron flow. Incorporating this element into the system critically alters its character, however, since it permits the sub-Poisson electrons flowing in the circuit to be converted into sub-Poisson photons by means of electron transitions. The key to the achievement of this effect is the replacement of the detector used in other feedback configurations with a structure that acts simultaneously as a detector and a source. The electrons simply emit sub-Poisson photons and continue on their way. In the absence of the feedback path, of course, the electrons would simply emit Poisson photons. Thus, the introduction of the electron feedback converts Poisson photons into sub-Poisson photons. The configuration in Fig. 1(b) is similar except that the (negative) feedback current modulates (gates) the light intensity at the output of the LED rather than the current at its input.

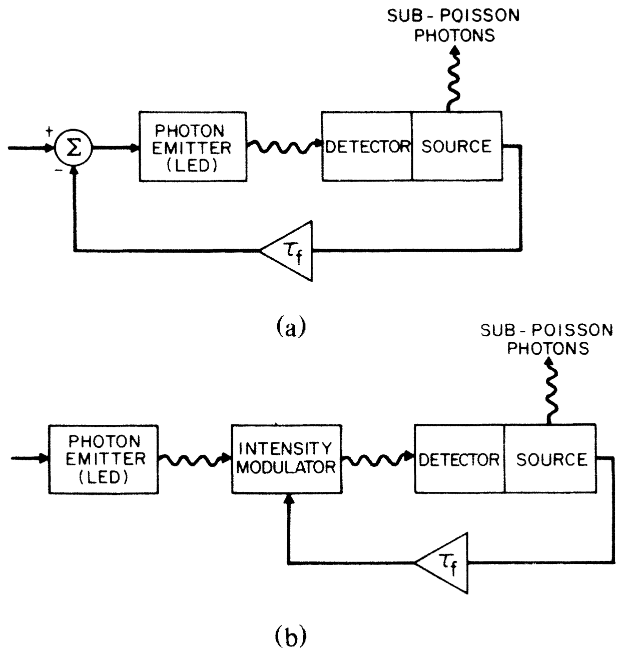

FIG. 1. Generation of sub-Poisson photons by means of negative feedback. The feedback produces sub-Poisson electrons in the detector-source which, in turn, generate sub-Poisson photons. (a) Negative feedback modulating the photon-emitter input current. (b) Negative feedback modulating the photon-emitter output light. Wavy lines represent photons; solid lines represent electron current. τ_f signifies the feedback time constant.

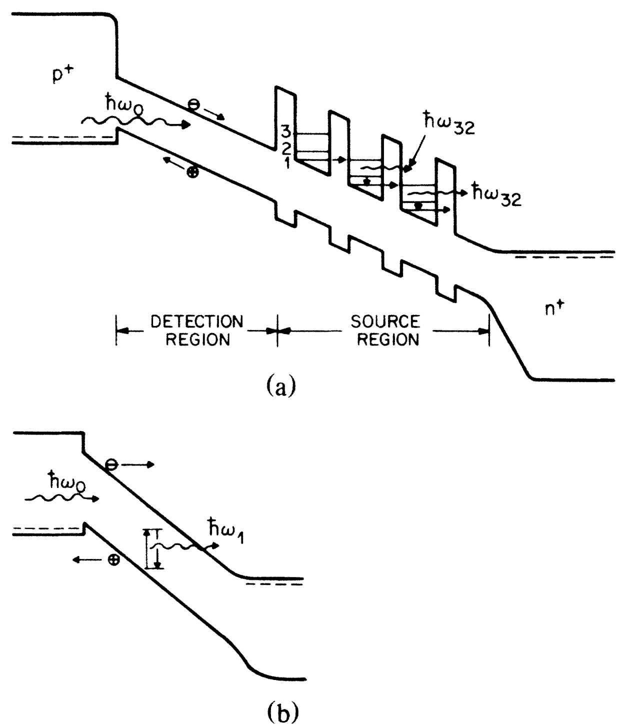

FIG. 2. (a) Band diagram of the quantum-well detector-source. The energy of the incident photon emitted by the LED is denoted $\hbar\omega_0$. The absorbing region (detection region) is of $Ga_{0.47}In_{0.53}As$ or GaAs, typically 1 μm thick. In the source region, the wells are $Ga_{0.47}In_{0.53}As$ or GaAs in the thickness range 150–300 Å. The barrier layers are of $Al_{0.48}In_{0.52}As$ (in the case of $Ga_{0.47}In_{0.53}As$ wells) or AlAs (in the case of GaAs wells) and should be in the thickness range 20–50 Å to achieve tunneling times < 1 psec. Photons of energy $\hbar\omega_{32}$ are emitted via transitions from level 3 to 2. The p^+ and n^+ wide-gap regions are of $Al_{0.48}In_{0.52}As$ (or AlAs). The interface between the i and n^+ regions is compositionally graded. (b) Energy-band diagram of a detector-source with electroluminescent centers that are impact excited by energetic photoelectrons, emitting photons with energy $\hbar\omega_1$.

In Fig. 2 we illustrate two possible solid-state detector-source configurations. The basic structure consists of a reverse-biased p^+-i-n^+ diode where the p^+ and n^+ heavily doped regions have wider band gaps than the high-field, light-absorbing and -emitting i region. This arrangement ensures both high quantum efficiency at the incident photon wavelength (to which the p^+ window layer is transparent) and high collection efficiency (due to the waveguide geometry) for the light generated by the electrons drifting in the i layer. An edge-emitting geometry is therefore appropriate. To maximize the collection efficiency, some of the facets of the device could be reflectively coated. Two light-generation schemes are explicitly considered here: single-photon dipole electronic transitions between the energy levels of the quantum wells [Fig. 2(a)] and impact excitation of electroluminescent centers in the i region by drifting electrons [Fig. 2(b)].

In the first scheme [Fig. 2(a)], the i region consists of a layer in which the incident photons are absorbed (detection region) and an adjacent quantum-well region in which photons are generated by sequential resonant tunneling (source region). Capasso, Mohammed, and Cho[14] have recently demonstrated the sequential resonant tunneling of electrons through a quantum-well superlattice consisting of 35 periods of $Al_{0.48}In_{0.52}As$ (140 Å) and $Ga_{0.47}In_{0.53}As$ (140 Å). The observation of this effect, first predicted in 1971 by Kazarinov and Suris,[15] has been made possible by the remarkable quality of superlattice structures recently achieved by the molecular-beam-epitaxy growth technique.

The structure presented in Fig. 2(a) is similar to that previously used in the resonant tunneling experiment.[14] The reverse-bias voltage applied to the detector is adjusted such that the potential-energy drop across the superlattice period (barrier plus well) is equal to the energy difference between the bottom of the third and first subbands of the quantum wells. Such discrete subbands (which have momentum dispersion in the plane of the layer) arise from size quantization perpendicular to the layers when the electron de Broglie wavelength is comparable to the well thickness.[16] Under such bias conditions electrons undergo resonant tunneling into the third energy level of the quantum wells and the device current exhibits a peak due to the enhanced tunneling probability. Once the electron finds itself in the third energy level, it relaxes by the emission of either phonons or infrared photons.

The relative probability of these two processes is an important parameter of the system because a nonradiative decay represents random deletion and this reduces the sub-Poisson character of the generated light.[17] The most important nonradiative process is scattering, by intersubband optical phonons, of the electron located at the bottom of the third energy level. This results in the electron finding itself in the $n=2$ subband after the emission or absorption of a phonon. (Once the electron has scattered to the second subband it nonradiatively relaxes to the bottom of the ground-state subband.) The intersubband optical-phonon–assisted electron transitions are much stronger than the acoustic-phonon–assisted transitions and have a rate which is typically several orders of magnitude greater than the radiative spontaneous emission rate from the $n=3$ to the $n=2$ level (this is estimated to be $\approx 10^7$–10^8 $\sec^{-1}$ at a wavelength $\lambda=10$ μm, in the 140-Å well structures considered in Ref. 14). This radiative transition is dipole in nature and the emitted light is polarized normal to the plane of the layers. These photons cannot be reabsorbed by ground-state electrons since $E_3-E_2 \neq E_2-E_1$. Indeed, this dipole transition has recently been observed in absorption between the ground and first-excited states of quantum wells.[18]

The probability that an electron undergoes a radiative transition (i.e., the radiative efficiency) η_r at the emission frequency $(E_3-E_2)/h$ can nevertheless be increased substantially by quenching of the optical-phonon–assisted transition. This may be accomplished by an appropriate increase of the well thickness thereby making the energy separation E_3-E_2 smaller than the optical-phonon energy (≈ 35 meV), in which case the device would emit in the middle infrared wavelength region. Another method to increase the radiative efficiency is to apply a magnetic field perpendicular to the layers. In the presence of the magnetic field, the electron states in the plane of the layer become quantized resulting in a manifold of discrete Landau levels. This total quantization of the electron wave function dramatically reduces the available density of states for scattering, thus quenching the intersubband transitions. Recent experiments by Ryan *et al.*[19] have indeed shown that, in the presence of a perpendicular magnetic field, the energy relaxation rate of an electron-hole plasma in quantum wells is reduced by many orders of magnitude. Although it is difficult to estimate precisely the radiative efficiency obtainable with the selective quenching of optical-phonon–assisted intersubband transitions and/or with the application of an external magnetic field, we expect that values between 0.01 and 0.1 should be achievable. We have applied the standard four-level–system rate equations to estimate that 1–10 nW of infrared power at a wavelength $\geqslant 10$ μm should be achievable for a photocurrent $\approx 10^{-5}$ A. Another suggested configuration, making use of electroluminescent centers impact excited by energetic photoelectrons,[20] is presented in Fig. 2(b). The use of a superlattice configuration in the *i* region could be useful in the enhancement of the impact-excitation probability.[21]

The ability of configurations such as these to generate sub-Poisson light requires a number of interrelations among various characteristic times associated with the system. Specifically, the condition $\tau_f \gg \tau_{\text{tr}}, \tau_{\text{resp}}$ must be obeyed, where τ_f is the feedback time constant, τ_{tr} is the transit time of the electrons and holes through the structure, and τ_{resp} is the response time of the detector-source. This condition ensures that the detector-source response is fast enough to be properly integrated by the feedback circuit. It is also required that $T \gg \tau_f$, where T is the counting (integration) time of the *external* detector that monitors the sub-Poisson light. This ensures that the photons are monitored for a time that is sufficiently long for the negative feedback to act on the rate of LED photon emissions. Finally, it is also required that $T \gg \tau_r$, where τ_r is the spontaneous-emission lifetime of the radiative transition. This assures that the photon emissions will be captured in the proper counting time interval.[2,22]

An estimate of the degree to which a light source is sub-Poisson (amplitude squeezed) is provided by the ratio of the photon-number variance to the photon-number mean (Fano factor), $F_n(T)=\text{Var}(n)/\langle n \rangle$. For sub-Poisson light, the condition $0 \leqslant F_n(T) < 1$ is obeyed; the closer $F_n(T)$ is to zero, the more sub-Poissonian is the light. The mechanism for the generation of sub-Poisson light described in this Letter can be characterized by a sub-Poisson electron counting process *e*, each event of which independently generates a random number of photons M in the source. The overall photon-number Fano factor $F_n(T)$ can then be represented in terms of the Fano factor for the electron number $F_e(T)$ and the Fano factor for the source random variable $F_M(T)$. The relationship is[17,22]

$$F_n = \langle M \rangle F_e + F_M, \tag{1}$$

where $\langle M \rangle$ is the average number of photons generated in the source by each electron.

For the case at hand it is reasonable to assume that the source random variable is Bernoulli distributed in each stage of the device,[22] with the probability of an electron giving rise to a photon denoted η_r. No generality is lost by consideration of the multilayer superlattice case, which consists of m independent stages. The source statistics will then take the form of a binomial random variable with $\langle M\rangle = m\eta_r$ and $\mathrm{Var}(M) = m\eta_r(1-\eta_r)$. In the presence of random deletion arising from other factors (e.g., finite geometrical photon-collection efficiency, absorption, external detection) and background or dark photons, these results remain valid upon the replacement of η_r by the quantity $\eta\beta$, where η is the overall quantum efficiency from electrons to detected photons and β is a factor representing the admixture of independent dark and/or background events.[17] In that case, F_n will be the Fano factor for the *detected* photons. (It may be useful to operate structures such as those discussed here at reduced temperatures to assure that $\beta \approx 1$ and to enhance the resonant tunneling current.) Equation (1) then provides

$$F_n - 1 = \eta\beta[mF_e - 1]. \qquad (2)$$

From Eq. (2) it is evident that sub-Poisson behavior may be discerned when $F_e < 1/m$. However, the lowest Fano factor is achieved when $m=1$. In this case, the photon counting process is simply a randomly deleted version of the electron counting process so that Eq. (2) reduces to its usual familiar form.[2,17,22]

Numerical estimates can be obtained for the degree of sub-Poisson behavior that is expected to be observable for the two structures discussed here, on the assumption that $\beta \sim 1$. For the superlattice device, η will be the product of the quantum efficiency of the *external* detector ($\eta_d \approx 0.8$), the geometrical collection efficiency of the emitted sub-Poisson photons ($\eta_g \approx 0.5$), and the radiative efficiency ($\eta_r \approx 0.1$). From the experiment of Machida and Yamamoto[9] we estimate that $F_e \approx 0.2$ (which is principally limited by the quantum efficiency of the detector in the detector-source combination). Thus, for this particular superlattice structure, Eq. (2) provides an overall Fano factor $F_n \approx 0.968$ for the detected sub-Poisson photons. The estimated Fano factor for the electroluminescent structure falls in the same range. These estimates provide a significant potential improvement over the value observed in the space-charge–limited Franck-Hertz experiment.[2] Lower values of the Fano factor can be achieved in structures that exhibit higher radiative efficiency. As indicated earlier, there is no fundamental limit that impedes this scheme from being used to produce an arbitrarily sub-Poissonian cw light source of arbitrarily high intensity.

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