The Quantum Optical Repeater

Yoshihisa Yamamoto

There has been a great deal of interest recently in the fundamental quantum properties of light and, in particular, practical applications of manipulating the quantum statistical properties of photons. Much of that interest has come from the optical precision measurements and communications field, which seeks to overcome the noise limit for signal transmission and reception that results from the fundamental quantum nature of light. Those seeking ever more precise measurement techniques are exploring the possibility of quantum nondemolition experiments, in which measurement back-action noise is diminished on the channel of interest with a compensating increase in the conjugate channel. What are the prospects at present for such devices?

Recently, Goobar *et al.* (*1*) and Roch *et al.* (*2*) independently demonstrated the quantum correlation between the photocurrent fluctuation of a semiconductor optical receiver and the output intensity fluctuation of a semiconductor light emitter driven by the photocurrent of the receiver. This means that the two fluctuations are correlated beyond the shot noise limit; this cannot be explained by a classical theory of light and must be a quantum effect.

The significance of these results (*1*, *2*) is not that they are another experimental demonstration of the quantum nature of light, but rather that, on the basis of the observed quantum correlation, both groups claimed that a "quantum optical repeater" can be constructed by combining a semiconductor optical receiver of high quantum efficiency (such as a photodiode) and a light emitter (such as a light-emitting diode or diode laser). This proposed device allows one to read the information of an incoming signal and also send (or regenerate) the identical signal without suffering from the signal-to-noise ratio (S/N) degradation.

A conventional optical repeater incorporating a beam splitter suffers from S/N degradation in both the readout channel and the throughput channel, because of vacuum fluctuations introduced by the beam splitter. The sum of the S/N ratios in the two channels is only equal to the S/N ratio of the incoming signal when the input signal is in a coherent state (that is, the quantum state of light closest to a classical electromagnetic field). This is the standard quantum limit (SQL) of an optical repeater (*3*). The present scheme features better performance than the conventional optical repeater, that is, the S/N ratio of each channel can be independently identical to the S/N ratio of the incoming signal. Thus, the device has been called a "quantum optical repeater."

If the photocurrent of the receiver in this arrangement is amplified by a low-noise electronic amplifier before driving the emitter, the intensity of the incoming signal can be amplified with additive noise much less than that imposed in a conventional (phase-insensitive) optical amplifier. When the input signal in a coherent state is amplified by an ideal optical amplifier, the S/N ratio of the output signal is degraded by 3 dB because of additive (quantum) noise generated in the amplifier. This

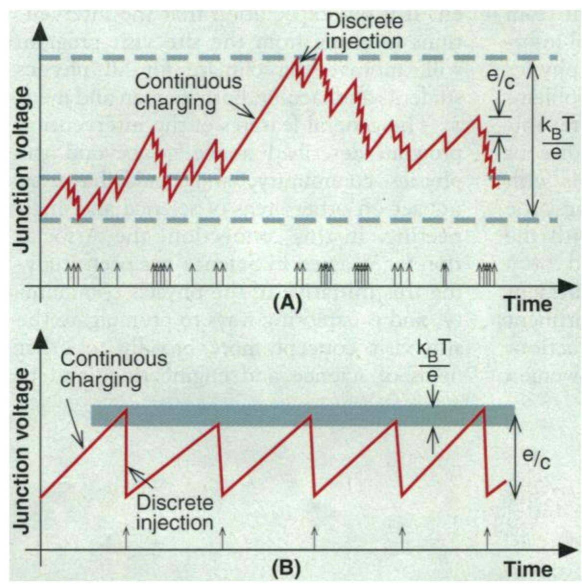

Fig 1. (A) The random evolution of a junction voltage produced by continuous uniform charging and discrete injection of carriers in a macroscopic *pn* junction ($e/C < k_BT/e$). **(B)** The regulated evolution of a junction voltage produced by continuous uniform charging and discrete injection of a single carrier in a microscopic *pn* junction ($e/C > k_BT/e$).

is the SQL of an optical amplifier (*3*). The proposed device also circumvents the SQL of an optical amplifier.

These functions of the proposed device resemble those of a quantum nondemolition (QND) measurement (*4*). The QND measurement of photon number allows one to monitor one quantum observable with an arbitrary accuracy without disturbing the free evolution of the measured observable (*5*). All of the back-action noise of the measurement is imposed on the conjugate observable and does not couple to the measured observable at all. The quantum state after the QND measurement can be predicted by von Neumann's projection postulate and, in this sense, is a "first kind measurement," as defined by Pauli.

In spite of its beautiful mathematical structure, realization of efficient QND measurements is not very promising. The proposed device potentially realizes the same functions of the QND measurement of photon number, even though it is based on complete destruction of an input quantum state and reconstruction of the identical output quantum state. It seems to be more promising and practical than any of the QND measurement schemes proposed so far. In fact, the performance reported in (*1*, *2*) is better than any QND measurement demonstrated in the past. But does the proposed device really operate as a photon number repeater or photon number amplifier in a single photon limit?

Unfortunately, the proposed device has a practical limitation in this point. It has been known for some time that a semiconductor light emitter of high quantum efficiency converts a noise-free constant current into a noise-free constant photon flux (*6*). The Johnson-Nyquist thermal noise generated in a large resistance can be made much smaller than the shot noise. This is the basic principle of the present device. However, this is true only when a large number of photons is measured for a fairly long time interval. The pump process in a semiconductor light emitter is the thermionic emission or tunneling of electrons or holes (or both) into an active layer across a *pn* junction depletion layer. This carrier injection process is inherently a stochastic process even though the junction is driven by a "quiet current."

A noise-free circuit current realizes a continuous charging of a junction (Fig. 1A). This results in linear increase in a junction voltage but does not guarantee a regulated electron (or hole) injection. Rather, a discrete carrier injection across the *pn*-junction depletion layer occurs randomly because the state of such a macroscopic *pn* junction is not modulated appreciably by a single carrier event. A junction voltage increase or drop caused by a single carrier charging or injection is e/C, where e is the charge of an electron and C is a depletion layer capacitance. This value is much smaller than the thermal voltage k_BT/e (where K_B is the Boltzmann constant and T is temperature) for a conventional *pn*

The author is at the ERATO Quantum Fluctuation Project, Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA.

junction light emitter. Therefore, a single carrier charging or injection event never affects subsequent events.

A continuous charging of unit charge e to the pn junction does not necessarily result in a single carrier injection, and so a subsequent single photon emission has no correlation with a single carrier charging by the receiver output photocurrent. Therefore, there can be no direct correspondence between a single photon detected by the receiver and single photon emission by the emitter. One may argue that if a pn junction is supplied with a unit charge e by the photocurrent, then a single photon should be emitted from the junction because of the energy conservation law. A single photon is certainly emitted as a result of the unit charging if one waits for a very long time, but then an emitted single photon is completely masked by many thermal photons emitted during the same time interval.

However, the collective effect of many carriers can still self-regulate the number of injected carriers in a macroscopic limit. A detailed calculation (*7*) indicates that the injected carrier number is regulated to below the Poisson limit only when the measurement time T_o is long enough or the current I is large enough so that the average number of carriers $n_e = (I/e)T_o$ exceeds $k_B TC/e^2$. The condition can be understood as the collective junction voltage increase or drop by n_e carriers, $(e/C)\ n_e$, being equal to the thermal voltage $k_B T/e$. For a typical pn junction light emitter with $C = 1$ nF and $T = 300$ K, this critical carrier number is on the order of 10^8. The observed intensity quantum correlation between an incoming and outgoing wave (*1, 2*) is indeed in this macroscopic limit. Hence, the proposed device cannot regenerate a signal energy with the accuracy Δn_e better than $(k_B TC/e^2)^{1/2} \approx 10^4$.

To reach the single photon limit, such as in an ideal QND measurement, the junction voltage increase or drop (e/C) by single carrier charging or injection must be much larger than the thermal voltage $k_B T/e$. In such a case, the continuous charging of a unit charge e and discrete injection of a single carrier have one-to-one correspondence (Fig. 1B) (*8*). The above requirement, $e/C \gg k_B T/e$, is known as the requirement for Coulomb blockade in a tunnel junction (*9*). Just as this condition must be met for regulated single electron tunneling (high-precision current standard) (*9*), single photon manipulation with a semiconductor pn junction also must satisfy this condition (*8*).

Given developments in nanostructure fabrication technologies, we can expect great effort in this area. A quantum optical repeater consisting of semiconductor receiver and emitter must meet the goal of a single photon manipulation before a QND measurement can be possible. Recent results, such as those in (*1, 2*), are steps along the way, but the goal still remains elusive.

References and Notes

1. E. Goobar *et al.*, *Phys. Rev. Lett.* **71**, 2002 (1993).
2. J. F. Roch *et al.*, *ibid.*, p. 2006.
3. Y. Yamamoto *et al.*, *Prog. Opt.* **28**, 89 (1990).
4. V. B. Braginsky *et al.*, *Science* **209**, 547 (1980).
5. For a recent review on experimental QND measurements, see P. D. Drummond *et al.*, *Nature* **365**, 307 (1993).
6. Y. Yamamoto *et al.*, *Science* **255**, 1219 (1992).
7. A. Imamoglu and Y. Yamamoto, *Phys. Rev. Lett.* **70**, 3327 (1993).
8. ———, *Int. J. Mod. Phys. B* **7**, 2065 (1993).
9. D. V. Averin and K. K. Likharev, *J. Low Temp. Phys.* **62**, 345 (1986).

Will Transgenic Crops Generate New Viruses and New Diseases?

Bryce W. Falk and George Bruening

Plant viruses cause significant losses of important food and fiber crops. To stop these harmful viruses, agriculturists have tried several strategies, including use of insecticides or other agents to reduce the number of virus vectors or removal of the plants that are the source of the virus. Other defenses include the use of virus-free plant propagation material and the introduction of resistance genes into crop species by traditional plant breeding. Each of these methods has its practical drawbacks, and their effectiveness varies from crop to crop, location to location, and even year to year. A recent and potentially powerful new approach is to express certain segments of plant virus genomes in transgenic plants, a procedure that confers resistance against the corresponding virus (*1, 2*). Is there risk in this method? A report by Greene and Allison in this issue of *Science* (*3*) clearly and elegantly shows that genomic recombination can occur when transgenic *Nicotiana benthamiana* plants expressing a segment of a cowpea chlorotic mottle virus (CCMV) genomic RNA are inoculated with a mutant CCMV that contains a deletion. The transgenic RNA of the plant and the genomic RNA of the virus are apparently available in sufficient quantities and in the proper form and place to allow recombination. Could such recombination produce dangerous new viruses? Greene and Allison cautiously conclude that "RNA recombination should be considered when analyzing the risks posed by virus-resistant transgenic plants."

Most known plant viruses have small genomes composed of single-stranded RNA, usually of 10,000 nucleotide residues or less. RNA-RNA recombination is a rare event in plant virus replication but presumably contributes to evolution of the viral genome (*4–6*). Indeed, under strong selective pressure for the recombinant RNA, intermolecular RNA-RNA recombination has been demonstrated for four groups of RNA plant viruses—alfalfa mosaic virus, bromoviruses, carmoviruses, and tombusviruses (*7–11*), and for the plant pararetrovirus cauliflower mosaic virus (*12*). RNA-RNA recombination occurs between closely related RNA molecules, but also between dissimilar RNAs—possibly at sites of similar RNA structure (*4, 13*).

Under usual agricultural conditions plant viruses have many opportunities to interact genetically. Viral genes are already distributed over vast acreages by insect and other natural virus vectors and by infected propagation materials (for example, seeds, seed potatoes, tree and vine cuttings). These infected plants can then be infected again by other viruses. These multiple, as well as single, infections occur commonly in both crop and weed hosts. For example, cucurbits {including melons, cucumbers, and squash [a genetically engineered, virus-resistant version of which may be released soon (*14*)]} are often doubly infected by viruses. Indeed, five independent viruses have been recovered from a single plant (*15*). Mixed infection probably occurs even more often than reported, because subliminal infections (*16, 17*) (in which inoculated cells become infected but the infection does not spread) go undetected. In fact, most plant viruses can infect most plant protoplasts, suggesting that individual plant cells can easily be infected by viruses that do not infect the whole plant. Mixed subliminal and conventional infections have likely already brought together combinations of virus genes that some have assumed could be in proximity only when a virus infects a plant that is transgenically expressing the genes of other viruses (*18*). Thus, recombination in the field, between a virus that cannot systemically infect a particular plant and viruses that do, does not have a zero probability.

The authors are in the Department of Plant Pathology and Center for Engineering Plants for Resistance Against Pathogens (CEPRAP), University of California, Davis, CA 95616, USA.