PROPOSAL FOR GENERATION OF AMPLITUDE-SQUEEZED LIGHT (ASL) FROM LASER DIODES WITH ELECTRONIC FEEDBACK

Indexing terms: Optics, Lasers and laser applications, Quantum optics

It is generally believed that the amplitude fluctuations of a light beam initially in the coherent state cannot be squeezed below those of shot noise by the simple arrangement of a beamsplitter and a detector, the current from the detector being fed back to the light source or to a modulator. A simple semiclassical theory shows that arbitrary amounts of squeezing can in fact be obtained if a negative optical-conductance device such as a constant-voltage-driven (non-self-oscillating) laser diode is used in place of a conventional detector.

Machida and Yamamoto[1] have shown that conventional laser diodes generate light with amplitude fluctuations squeezed below those of shot noise when a cooled resistance of large value is inserted into the driving circuit. This nonclassical state of light is of practical interest, e.g. for the detection of small optical absorptions. The amount of squeezing remains modest because of various imperfections internal to the diode. It would be of great importance to be able to convert efficiently beams of light initially in the coherent state into ASL, preferably without acting back on the light source and over a broad band. The quantum nondemolition technique that has been proposed[2] to achieve this result is difficult to implement, as it relies on the rather weak Kerr effect.

The first idea that comes to mind is to use a beamsplitter and to detect part of the incident light beam. The amplified detected current modulates the remaining light in such a way that its fluctuations would be reduced. Electronic amplification can in principle be achieved with negligible added noise at low temperatures. The amplitude modulator also introduces negligible noise because it needs insert only small losses in the optical path. The key difficulty relates to the beamsplitter. While amplitude fluctuations of classical origin (e.g. due to temperature changes) can be greatly reduced by the above beamsplitter arrangement, the fundamental fluctuations of the usable (out-of-loop) photons are always increased rather than reduced by feedback.[3] The semiclassical laser diode theory recently reported[4,5,†] shows that light initially in the coherent state can in fact be converted into ASL if a negative optical conductance device is used instead of a conventional detector.

Aside from usual electrical engineering formulas, the laser theory rests on the postulate that a Gaussian complex random current $I_n(t) \equiv c(t) + is(t)$ of spectral density

$$S_c = S_s = |G| \qquad S_{cs} = 0 \tag{1}$$

(in units such that $h\nu = 1$, where h denotes Planck's constant and ν operating optical frequency) is associated with any conductance G. Double-sided spectral densities and root-mean-square voltages or currents are used. This is the fluctuation-dissipation theorem for quantum noise: $kT \ll h\nu$.

One also needs the particle-conservation law

$$J(t) = \mathrm{Re}\,\{V^*(t)[G(t)V(t) - I_n(t)]\} \tag{2}$$

where J is the electronic current injected into the diode, V the optical voltage across the conductance G which models the active medium gain or loss, and the electron charge is set equal to unity. Eqn. 2 is applicable at small baseband frequencies and for ideal diodes or detectors.

The proposed arrangement, shown in Fig. 1, could be implemented with existing optical components. A light beam in the coherent state enters into a circulator (or its optical analogue using magnetised YIG crystals) at port 0, and is directed towards a conductance G with $-1 < G < \infty$ (port 2).

† ARNAUD, J.: 'Semiclassical theory of amplitude noise for laser diode with electronic feedback'; unpublished

The characteristic conductance of the transmission lines (free space in optics) is taken as unity. The field reflection

$$r = (1 - G)/(1 + G) \tag{3}$$

is larger than unity if G is negative, and smaller than unity otherwise. The wave reflected from G constitutes the useful outgoing beam (port 1).

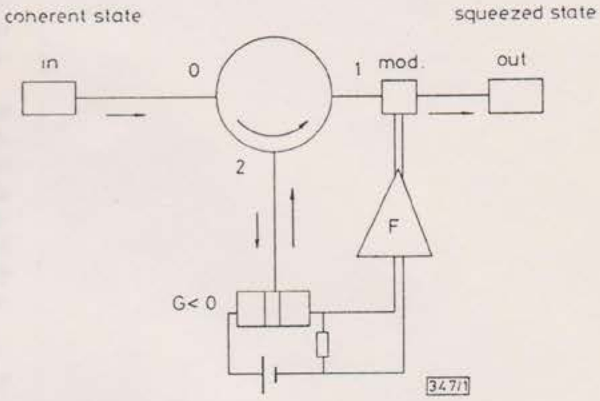

Fig. 1 *Schematic diagram of proposed arrangement*

Light in coherent state enters circulator through port 0, and is directed to a constant-voltage-driven optical amplifier labelled $G < 0$, at port 2. When current from this optical amplifier (sensed by small resistor) is electronically amplified and used to modulate output beam, amplitude fluctuations may be squeezed below shot noise

In practical terms, the negative conductance G could be a (non-self-oscillating) laser diode with one facet totally reflecting driven by a constant DC voltage. The energy spacing between quasi-Fermi levels then remains approximately constant, and this implies that the carrier number and optical conductance are also constant. The generation of optical power in the mode is supposed to be much larger than the generation of optical power into other (mainly radiation) modes. The driving current is sensed by a small resistor and electronically amplified.

Eqn. 2 leads† to the following expressions for the fluctuation j_1 of the power in the outgoing beam and the fluctuation j_2 of the current generated at port 2:

$$j_1 = r(1 + r)c_2 - r^2 j_0 \tag{4a}$$

$$j_2 = -r(1 + r)c_2 - (1 - r^2)j_0 \tag{4b}$$

where r is defined in eqn. 3 and j_0 is the fluctuation of the current injected into the original laser source. Because this source is supposed to deliver a coherent state with unity average power ($V = 1$), the spectral density of j_0 is unity. In eqns. 4 c_2 is the real part of the random current associated with the conductance G in port 2. According to eqn. 1 the spectral density of c_2 is equal to G if $G > 0$, and $-G$ if $G < 0$.

We first note from eqns. 4 that the particle conservation law initially postulated holds ($j_0 + j_1 + j_2 = 0$; all currents are defined as positive if outgoing) and that the outgoing beam exhibits the fluctuations of a coherent state, $S_1 = r^2 \equiv R$, as expected, if $G > 0$ (also, $S_2 = 1 - R$ and j_1, j_2 are uncorrelated). If $G < 0$ the spectral density S_1 exceeds R and this is the opposite of what we want. However, when the current j_2 is amplified and fed into the amplitude modulator shown in Fig. 1, the situation changes drastically. The fluctuation in the outgoing optical beam is now $j'_1 = j_1 + Fj_2$, where F is the feedback factor, the time delay being neglected. From the above expressions for j_1 and j_2 we easily derive that the spectral density S'_1 of the modulated outgoing beam is

$$S'_1/R = 1 + F^2(1 - R)/R \qquad R \leq 1 \tag{5a}$$

$$S'_1/R = 2R - 1 + 4F(1 - R) + F^2(2R^2 - 3R + 1)/R \qquad R \geq 1 \tag{5b}$$

The result in eqn. 5*a* shows that no improvement can be obtained from feedback when $R < 1$ or $G > 0$. Eqn. 5*b* is the new result. It shows that for any value of R larger than unity

($G < 0$) there is a value of F that minimises the amplitude fluctuations of the outgoing beam. For that optimum F-value

$$(S'_1/R)_{opt} = 1/(2R - 1) \tag{6}$$

is smaller than unity, that is, ASL has been generated. If $R = 1{\cdot}5$, for example, the power fluctuations of the outgoing beam (classically considered as resulting from the signal shot noise and the beat between the signal and the optical power spontaneously generated in the mode by the negative conductance amplifier[6]) are half those of shot noise.

A simple semiclassical theory (which can be trusted because it agrees with quantum theory for relevant configurations previously treated†) thus indicates that it may be possible to squeeze the amplitude fluctuations of a light beam initially in the coherent state below those of shot noise. This is accomplished with the help of a constant-voltage-driven optical amplifier. The current from that amplifier is electronically amplified and fed to an optical modulator. The optimum conditions have been determined.

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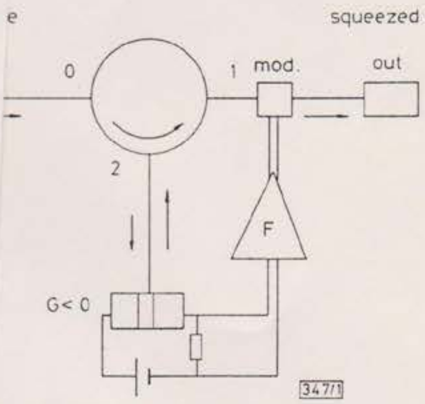

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