COHERENT-STATE OPTICAL AMPLIFIER: A PROPOSAL

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A new kind of phase-insensitive optical amplifier is proposed whose output is in the coherent state (ideal laser light) if the input is in the coherent state. In-phase and quadrature modulations are preserved in absolute values. Both modulations can be tapped off. The amplifier employs conventional optical amplifiers, electrical feedback, and all-pass filters. Remarkably, these properties hold when either linear or nonlinear optical amplifiers are employed.

It is well known that light from lasers operating well above threshold is in the coherent state (that is, photon emission times are statistically independent) if we consider only time intervals that are small compared with the cavity photon lifetime, and that light remains in the coherent state if it is attenuated. Unfortunately conventional (linear, phase insensitive) optical amplifiers add in-phase and quadrature fluctuations. For a power gain G, the output-fluctuation spectral densities are at best $2G - 1$ above the shot-noise level. Accordingly, fluctuations build up in a sequence of optical amplifiers and fibres [1]. Furthermore, amplitude fluctuations may be converted to phase fluctuations owing to the Kerr effect of the fibre.

It was shown previously [2] that the spectral density of the outgoing amplitude fluctuations may be *reduced* by a factor $2G - 1$ if the current driving the (semiconductor laser) amplifier is fed forward to an amplitude modulator, coherent states at the input being converted into minimum-uncertainty squeezed states at the output. A result not reported before is that feedback (instead of feedforward) preserves minimum uncertainty even if the input is not in the coherent state.

In the present proposal, phase rather than amplitude modulators are employed for two reasons. One is that questions regarding the optical losses of amplitude modulators no longer arise, at least in principle. The other is that we to control both quadratures equally. However, a detuned all-phase filter (DAPF) is now needed to exchange in-phase and quadrature components. The DAPF consists of a weakly coupled ring-shaped fibre, slightly detuned from the carrier frequency. The operation of a similar device was demonstrated in Reference 3 (with some optical gain to compensate for residual losses).

The proposed coherent-state optical amplifier (CSA) is phase-insensitive with respect to modulation and noise. Output light is in the coherent state if the input light is in the coherent state. Small-amplitude in-phase and quadrature modulations of the light beam are preserved in absolute value while the modulation indices decrease in proportion to the gain. The two modulations are measured with the same signal-to-noise ratio from electrical currents. Note that CSAs are quite different from quantum optical taps whose purpose is to tap off in-phase modulation without affecting the corresponding fluctuation, the other quadrature being much degraded [4].

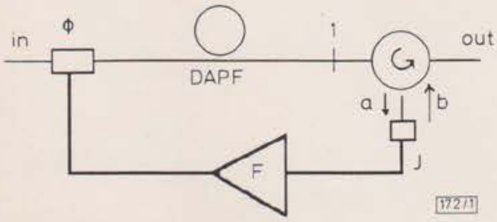

Fig. 1 *Schematic diagram of phase-squeezing amplifier (PSA)*

The input light is phase-modulated (Φ) and the optical carrier is 90° phase-shifted by a detuned all-pass filter (DAPF). Light then enters the optical amplifier (negative conductance and optical calculator) whose driving electrical current J is amplified and fed to the phase modulator. The proposed coherent-state amplifier consists of two such PSAs, one with gain G and the second with gain $2 - 1/G$

——— optical fibre
——— electrical feeder

A CSA consists of two phase-squeezing amplifiers (PSAs) in cascade, the first with gain G and the second with gain $G^\circ = 2 - 1/G$. As shown in Fig. 1, a PSA consists of an optical amplifier whose pump current is fed back to a phase modulator, with a DAPF inserted. The optical amplifier is best modelled as a negative conductance, the incident and reflected waves being separated with the help of an optical circulator.

The principle of operation is established on the basis of a commuting-variable theory that agrees with quantum theory for large particle numbers [5, 6]. For simplicity only low frequencies and negligible spontaneous carrier recombination and phase-amplitude coupling are considered.

We now clarify our notation. Real and imaginary parts of complex numbers are denoted by primes and double primes, respectively. Wave amplitude 'a' (such that $|a|^2$ is the photon rate) is written as $\langle a\rangle + \delta a + \Delta a$, where the average $\langle a\rangle$ is considered real and the peak modulation δa and noise Δa (both complex) are small. Averaging signs are omitted when no confusion may result. $2a\,\delta a'$ is the photon rate modulation. Double-sided spectral densities of $2\,\Delta a'$ and $2\,\Delta a''$ are denoted X and Y, respectively. For light in the coherent state, $X = Y = 1$. Either X or Y may be less than unity (squeezing) but $XY \geq 1$. We define normalised signal-to-noise ratios (SNR) as $s' \equiv (2\,\delta a')^2/X$ and $s'' \equiv (2\,\delta a'')^2/Y$, and for electronic rates J, $s_j \equiv (\delta J)^2/S_{\Delta J}$. Subscripts *in* and *out* refer to the PSA input and output.

With optimised feedback the following relations between input and output fluctuations of a PSA are found to hold (see the Appendix):

$$Y_{out} = G - 1 + GX_{in} \qquad 1/X_{out} = G - 1 + G/Y_{in} \quad (1)$$

It follows from eqn. 1 that minimum uncertainty is preserved, i.e. the product $X_{out}\,Y_{out} = 1$ if $X_{in}\,Y_{in} = 1$.

Let this PSA be followed by a second PSA with gain G° whose inputs are the outputs of the first one, and the outputs are denoted X, Y. We have, similar to eqn. 1,

$$Y = G^\circ - 1 + G^\circ X_{out} \qquad 1/X = G^\circ - 1 + G^\circ/Y_{out} \quad (2)$$

If we select

$$G^\circ = 2 - 1/G \quad (3)$$

it follows from eqns. 1–3 that light in the coherent state at the input $(X_{in} = Y_{in} = 1)$ remains in the coherent state $(X = Y = 1)$ at the output, but is amplified by a total gain $G_t = 2G - 1$. We can also show that the modulations $2a\,\delta a'$ and $2a\,\delta a''$ are unaffected by the CSA, but the modulation indices are reduced because the average rate is amplified. The SNRs of the outgoing optical beam relative to the input values are

$$s'_{out}/s'_{in} = s''_{out}/s''_{in} = 1/(2G - 1) \quad (4a)$$

The electrical current driving the optical amplifiers can be tapped without perturbation. It is easily established that the average electronic rate is $(G - 1)R$ for both PSAs, if R denotes the input rate. The electronic rate J from the first PSA provides information about the phase, and the electronic rate J° from the second PSA provides information about the amplitude. If we denote s_j and s_j° the corresponding SNRs we obtain

$$s_j/s''_{in} = s_j^\circ/s'_{in} = (G - 1)/(2G - 1) \quad (4b)$$

When the G value is increased a higher signal-to-noise ratio is obtained locally, but a lower one is transmitted further along the optical fibre.

In conclusion, we have shown theoretically that phase-insensitive optical amplifiers that preserve coherent states could be realised with semiconductor technology. It is remarkable that identical results are obtained with nonlinear amplifiers (see the Appendix). The phase of the output optical beam would follow input phase variations, but only slowly because of the narrowband DAPF. The proposed device could find application to sensors where amplitude and phase information are both needed, part of the information being employed locally and part of it being transmitted. For nonideal devices, consideration should be given to spontaneous carrier recombination, an effect that can be minimised with microcavities.

Appendix: The purpose of this Appendix is to prove eqn. 1. Consider first an active element with complete population inversion. Let $V\sqrt{(2h\nu)}$ and $I\sqrt{(2h\nu)}$ denote the complex voltage and current at optical frequency ν. The rate $R \equiv$ real (V^*I) at which photons are emitted (equal to the rate J at which electrons are absorbed under ideal conditions) is proportional (constant A) to the carrier number n, which is a constant for constant-voltage drives, and to the optical intensity $P \equiv V^*V$, plus an internal noise source r'

$$R = J = AnP + r' \qquad S_{r'} = \langle R \rangle \quad (5)$$

The spectral density of r' in eqn. 5 follows from the quantum master equation in the large-particle-number limit, or plausible intuitive arguments [6].

Eqn. 5 is readily converted into a relation between first-order variations of incident and reflected waves, a and b. Assuming for simplicity that the transmission-line characteristic admittance is unity, we set $V = b + a$, $I = b - a$, and obtain the real part of the following relations (linear optical amplifiers), with subscript 1 at the input

$$x_{out} = gx_1 + u' \qquad S_{u'} = G - 1 \quad (6a)$$

$$y_{out} = gy_1 + u'' \qquad S_{u''} = G - 1 \quad (6b)$$

where $x_1 + iy_1 \equiv 2\ \Delta a$, $x_{out} + iy_{out} \equiv 2\ \Delta b$ and $g = \sqrt{(G)}$, $u' \equiv r'/a$.

The in-phase component x_{in} is equal to y_1 because it is unaffected by the phase modulator (see the PSA shown in the Figure) and because the detuned all-pass filter interchanges the two quadratures. Considering further that x_{in} and u'' are independent, eqn. 1*a* follows from eqn. 6*b*.

We now prove eqn. 1*b*. A term $F\,\Delta J$ is added to the quadrature fluctuation y_{in}, where F denotes the feedback factor and ΔJ the fluctuation of the electronic rate driving the optical amplifier

$$x_1 = y_{in} + F\,\Delta J$$

$$\Delta J/a = \Delta(|b|^2 - |a|^2)/a = gx_{out} - x_1 \quad (7)$$

noise from the electrical amplifier being neglected (low temperature operation). Solving eqn. 7 for x_1 we obtain

$$fx_1 = g(1 + f)x_{out} - y_{in} \qquad f \equiv -(1 + Fa) \quad (8)$$

If we introduce this result in eqn. 6*a* and solve for x_{out} we obtain

$$(f + \gamma)(G - 1)x_{out} = gy_{in} - fu' \qquad \gamma \equiv G/(G - 1) \quad (9)$$

Because y_{in} is independent of u' (spectral density given in eqn. 6*a*) we obtain

$$(f + \gamma)^2(G - 1)X_{out} = \gamma Y_{in} + f^2 \quad (10)$$

Eqn. 1*b* follows from eqn. 10 when we observe that $f = Y_{in}$ is the feedback value that minimises X_{out}, irrespective of the G value.

In general (nonzero electrical impedance of the semiconductor amplifier driver or spectral-hole burning) n should be considered a function of R and a nonlinearity factor $\kappa \equiv -(n/R)\ dn/dR$ be introduced. We then obtain in place of eqn. 6*a* [6]

$$(1 + \kappa g)x_{out} = (g + \kappa)x_1 + u' \qquad S_{u'} = G - 1 \quad (11)$$

while eqn. 6*b* is unaffected. Proceeding as before we find that eqn. 1 remains valid for any κ value. The result can be further generalised to k-photon processes.

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