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Abstract

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REGENERATIVE OPTICAL QUANTUM AMPLIFIER

As in any quantum amplifier ($^{1-3}$), amplification in an optical quantum amplifier occurs due to induced emission in a certain medium with negative temperature. The present work contains the principal results of a study of sensitive regenerative optical quantum amplifiers (ROQA), i.e., optical amplifiers with positive feedback.

1. Experimental setup. The ROQA studies were carried out using an apparatus whose block diagram is shown in Fig. 1. As the signal source an OQG on ruby with modulated Q was used (^{4}). Modulation of the Q in the driving generator (one radiation spike) greatly facilitated the measurements, since the shape, duration, energy, and consequently the power of the amplified signal were known in advance. In addition, modulation of the Q in the driving OQG made it possible to localize the amplified signal precisely in time, which facilitated investigation of the time characteristic of the OQA. Attenuation of the OQG signal was carried out by neutral light filters Φ, which were calibrated beforehand. To reduce the divergence of the signal beam a collimator T (theodolite) was used. The diameter of the amplified beam was regulated by an iris diaphragm D. The ROQA operated in two regimes: without modulation of the resonator Q and with modulation of the latter.

Fig. 1. Block diagram of the apparatus

Photomultipliers were used as receivers; signals were recorded on a dual-beam oscilloscope. For time synchronization of the firing of the OQG and ROQA lamps with the oscilloscope sweep, a synchronizing device was used.

2. Gain coefficient of some regenerative OQA schemes. In an OQA with a resonator of the usual plane type, the input of the signal to be amplified was performed directly through a semitransparent mirror with reflection coefficient r_1, and the output through the second mirror with reflection coefficient r_2. The power gain coefficient of such a system G is

$$G = \frac{k(1-r_1)(1-r_2)}{1-k^2 r_1 r_2}, \tag{1}$$

Fig. 2. Unidirectional ROCG scheme.

Figure 1: Fig. 2. Unidirectional ROCG scheme.

Fig. 3. Dependence of the gain coefficient by power G on the gain coefficient per pass for different values of the feedback r (reflection coefficient of the semitransparent mirror).

Figure 2: Fig. 3. Dependence of the gain coefficient by power G on the gain coefficient per pass for different values of the feedback r (reflection coefficient of the semitransparent mirror).

where k is the gain coefficient per pass (^{5}).

In practice it is more convenient to extract the energy from the resonator by means of an auxiliary plate with reflection coefficient r, placed inside the resonator. The gain coefficient when summing both outputs of the ROQA is

$$G = \frac{(1 - r_1)r}{1 - k^4(1 - r)r_1}\,[1 + k^2(1 - r)]. \tag{2}$$

Such systems are simple to adjust; however, it is necessary to select the quantities k, r_1, r_2, and r very accurately so that G has the specified value under strong

regeneration. In addition, the approach to the generation threshold in such schemes is very critical, and obtaining a high gain coefficient at large regeneration is a rather difficult task.

Its solution is considerably facilitated by using, as the ROCG resonator, the unidirectional scheme shown in Fig. 2. In such a scheme the beam being amplified travels in the resonator along a closed path (for example, a triangle) in one direction. The input of the signal to be amplified is accomplished through a semitransparent mirror with reflection coefficient r.

Fig. 2. Unidirectional ROCG scheme. Z_1, Z_2—opaque mirrors; P—active medium; Π—semitransparent mirror with reflection coefficient r; PRN—optical receiver (photomultiplier); M—system for modulating the Q-factor; S_2—output signal.

Fig. 3. Dependence of the gain coefficient by power G on the gain coefficient per pass for different values of the feedback r (reflection coefficient of the semitransparent mirror). a—theoretical curves for a unidirectional ROCG; b—theoretical curves for a plane resonator; points—experimental values ($r = 0.1$) for the ROCG according to the scheme of Fig. 2.

Such a directional ROCG scheme has a number of advantages over the preceding ones. Indeed, the ROCG gain coefficient in this case is

$$G = r + \frac{k(1-r)^2}{1-kr}, \tag{3}$$

i.e., $G > 1$ for any $k > 1$ and $0 < r < 1$. In addition, in the denominator of (3) the product kr enters linearly. Therefore the approach to the generation threshold is more "soft." In other words, such a scheme is less critical to fluctuations of k and r, which considerably facilitates obtaining a stable gain coefficient.

Further, since the input and output of such a system are spatially separated, and the amplified signal travels in one direction, it is possible to connect several such amplifiers in series without special decouplings between stages. The block diagram for measuring the gain coefficient corresponds to Fig. 1. As already noted, an OQG with modulated Q-factor was used as the source. After passing through the calibrated attenuating filter Φ, the collimator T, and the diaphragm D, the signal to be amplified entered the ROCG and, after amplification, reached FEU-II, which was used as the receiver. Part of the signal before the ROCG was branched off by means of plate P to photomultiplier FEU-I, which was used to monitor the magnitude of the input signal. The signals from the outputs of both FEUs were fed to a two-beam oscilloscope DO, and the oscillograms were photographed. This method made it possible to measure both G and k (the single-pass gain coefficient), to determine the stability of G and k, and also their dependence on various parameters. These parameters were: pump energy, pump time (the time interval between ignition of the ROCG lamp and arrival of the amplified signal), feedback coefficient ···

coupling, determined by the magnitude of the mirror reflection coefficient r. The measurement results ($r = 0.1$) for the ROQA scheme corresponding to Fig. 2 are given in Figs. 3 and 4 together with the theoretical curves and showed satisfactory agreement with the latter.

3. Stabilization of the gain coefficient in an ROQA by the method of modulating the resonator Q. A very promising way of improving the parameters of a regenerative OQA is modulation of the feedback in the resonator (Q modulation). Q modulation makes it possible to prepare in advance a state with negative temperature. This eliminates fluctuations of the gain coefficient per pass (and, consequently, of the total gain coefficient of the ROQA), since in this case G does not depend on the pump power and is determined by the energy stored in the crystal by the time the signal arrives. In addition, the state with negative temperature, in the absence of feedback, is preserved longer than in the presence of the latter, which is quite clear from physical considerations. In other words, the method of Q modulation makes it possible to "hold" the state with negative temperature until the arrival of the signal to be amplified, provided, of course, that this time does not exceed the radiative lifetime of the active particles in free space.

Fig. 4. Dependence of the gain coefficients in power k and G (1—theory, 2 —experiment) on the pumping time τ of the amplifying crystal. Experimental

Fig. 4

Figure 3: Fig. 4

points: *a*—without Q modulation of the ROQA resonator; *b*—with Q modulation of the ROQA resonator; *c*—when measuring k.

The results of the corresponding measurements are presented in Fig. 4. As is seen from this figure, the gain coefficient for an ROQA without Q modulation decreases with time faster than the corresponding gain coefficient for an ROQA with Q modulation.

4. Sensitivity of the OQA. Measurement of the sensitivity of the OQA was carried out according to a scheme analogous to that for measuring the gain coefficient (Fig. 1). The difference was that the distance R from the ROQA output to the receiving photomultiplier FEU-11 was chosen as large as possible in order to reduce the influence of spontaneous radiation from the excited crystal entering nonaxial modes of the ROQA resonator. The receiving diaphragm d served the same purpose. To eliminate the background of the pump lamp, the latter was extinguished by a special device at the moment preceding reception. The value of the sensitivity of such a system can be estimated as follows. The angular aperture of the receiving device under consideration is $\Omega = (d/R)^2$. The maximum order of a nonaxial mode entering the angle Ω is determined from the relation

$$\frac{m\lambda}{b} \ll \frac{d}{R},$$

where b is the transverse dimension of the resonator and λ is the wavelength.

If one takes into account that the angular distance between nonaxial modes is λ/b, then the number of nonaxial modes corresponding to each axial mode is

$$\left(\frac{d/R}{\lambda/b}\right)^2.$$

The total number of modes corresponding to the angular aperture of the receiving device will be

$$N = N_a \left(\frac{d/R}{\lambda/b}\right)^2, \tag{4}$$

where $N_a = \dfrac{\Delta\nu_l}{c/2L}$ is the number of axial modes; L is the resonator length; $\Delta\nu_l$ is the linewidth; c is the speed of light. Substituting into (4) the values of

$\Delta\nu_l, L, d, R, \lambda, b$, we obtain the value N. The expected value of the sensitivity in this case (for a signal-to-noise ratio ~ 1) will be, in accordance with (3),

$$P_{\text{sh}} = Nh\nu\Delta\nu_p. \tag{5}$$

Substituting into this expression the value $\Delta\nu_p$ (which corresponds to a resonator quality factor $Q = \dfrac{\nu}{\Delta\nu_p}$), we obtain the magnitude of the noise power in the resonator that enters the receiver.

Measurements showed that the regenerative optical quantum amplifier senses a signal whose power (for a signal-to-noise ratio at the receiver output ~ 1) is of the same order as the theoretical value calculated from formula (5).

5. **Measurement of the passband of the regenerative optical quantum amplifier.** The passband of the optical quantum amplifier was measured by a method analogous to that used in radio engineering: the generator frequency was varied and the dependence of the gain coefficient on frequency was measured. To change the generation frequency of the optical quantum generator, the temperature shift of the line in ruby [6] upon cooling the crystal was used. From the measured dependence of the gain coefficient on temperature $G(T)$, the amplifier passband was determined as

$$\Delta\nu_{\text{ROQA}} = 2(\nu_0 - \nu)\big|_{G=\frac{1}{2}G_0},$$

where ν_0 is the frequency corresponding to the middle of the central part of the line at room temperature; ν is the generation frequency determined by the temperature of the cooled generator crystal; G_0 is the gain coefficient at the same (room) temperature of the amplifying and generator crystals.

Measurements showed that the ROQA passband at $G = 25$ is 5 cm^{-1}.

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