Holographic preamplifier for a quantum amplifier

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A sequential amplification in holographic and quantum amplifiers of a weak optical signal, with an initial intensity below the noise level of the active element of a laser, is proposed. An experimental implementation has been reported.

Quantum amplifiers which make use of stimulated emission in media with a population inversion are used widely for amplifying light beams. Amplifiers which use the active media of metal-vapor lasers exhibit significant gain values and can raise the brightness of a weak input signal by a factor of 10^3–10^4. These media can thus be used as brightness amplifiers in optical systems.[1] The noise of an amplifier of this sort stems from a spontaneous emission on the working (laser) transition. The minimum level of the input noise is about one photon per mode. Because of possible light scattering in optical systems which use brightness amplifiers, the actual level of the input noise may be higher than this intrinsic noise of the amplifier.

Another possibility for increasing the brightness of light beams, based on some other physical principles, involves the use of amplification in a coherent, frequency-degenerate four-wave mixing. One version of an amplifier of this sort mixes a signal wave with a more intense pump wave, which is coherent with the signal wave, in photorefractive crystals with a nonlocal response.[2] In these crystals, the refractive-index grating is displaced from the interference field by a quarter of a period; the effect is a coherent amplification of a weak signal wave at the expense of the pump wave, without large-scale distortions of the wave front. Photorefractive crystals can also be used to amplify optical signals over a wide spectral range. With the photorefractive crystal $BaTiO_3$, which is the best one available today, holographic amplifiers of this sort can achieve a significant brightness increase [by a factor $\sim 4\times 10^3$, even for weak, continuous light beams, with an intensity of 10^{-8} W/cm (Ref. 3)].

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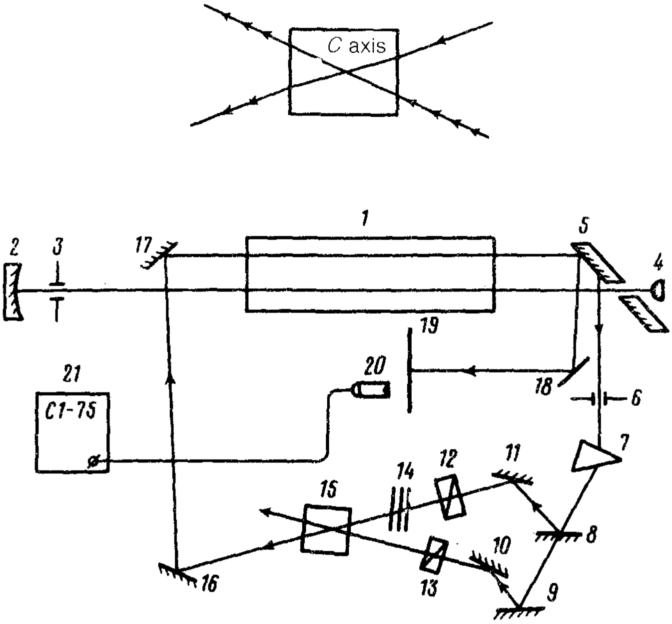

FIG. 1. Experimental layout.

In the present letter we demonstrate that it is possible to amplify a coherent signal with an intensity below the actual noise level of a copper-vapor active element through the use of a coherent holographic preamplifier which uses a photorefractive barium-sodium niobate crystal. For the experiments we selected the active element of a commercial UL-102 amplifier, in whose design special measures have been taken to substantially reduce the intensity of parasitic scattered light at the input to the amplifier.

The experimental layout is shown in Fig. 1. The signal beam is directed to the preamplifier, into which a coherent pump beam is also introduced. The output beam then enters the active element of the UL-102 (the pulse repetition frequency is 10 kHz, and the working wavelengths are 0.51 and 0.58 μm; Ref. 1) for further amplification. In the case of an amplification of images on transparencies, additional optical elements are placed in the path of the signal beam.

The signal beam and the coherent pump beam for the preamplifier are formed from the output from an auxiliary laser, which uses the same copper-vapor active element 1 as is used for the amplification. An unstable telescopic resonator formed by mirrors 2 and 4, with focal lengths of 250 cm and 2–1.5 cm, is used to improve the spatial coherence of the laser beam. A diaphragm 3 with a diameter of 0.3 cm is positioned inside this resonator. The temporal and spatial coherence of the output from a laser of this type is sufficient for writing dynamic gratings and for amplifying beams in barium-sodium niobate crystals.[4]

Mirrors 5, 8, 9, 10, and 11 bring the pump and signal beams together in the sample of the barium-sodium niobate crystal, 15, whose optical axis is oriented in the plane of convergence of the beams. A transmission dynamic grating with a wave vector **k** approximately parallel to the *C* axis is written in the photorefractive crystal. After passing through diaphragm 6, the light is sent to a dispersive prism 7, which selects a green line from the emission beam. Glan prisms 12 and 13 select a polarization of the incident beams to excite extraordinary waves in the crystal. A set of optical filters 14 is introduced in order to control the intensity of the signal input beam. The beam amplified in the photorefractive crystal is returned by mirrors 16 and 17 to active medium 1, amplified there, and coupled out by mirror 18 for visual observation on screen 19. Alternatively, it is detected by a photodiode 20 and an oscilloscope 21 (S1-75).

An amplification of a light beam whose power at the entrance to the holographic element was below the noise level of active element 1 has been achieved experimentally in this arrangement.

With the reference beam blocked, the intensity of the signal input beam at the photorefractive crystal was lowered by filters 14 to the point at which the collimated amplified beam on screen 19 disappeared against the background of the noisy emission of active medium 1. When we turned the pump beam back on, i.e., introduced the additional preamplification, we observed the appearance of a clearly visible amplified beam on the screen. In quantitative measurements, we judged an output signal detectable if its level was 20% above the average noise level.

The results show that this two-stage system can amplify a signal with an intensity of 3×10^{-7} W/cm^2, while without the preamplifier the minimum intensity of an input signal is no less than 2×10^{-6} W/cm^2. These figures refer to an initial signal beam with a divergence $\sim3\times10^{-4}$ rad; the divergence is roughly doubled after the photorefractive crystal. The overall amplification of the two-stage amplifier is 270×.

The possibility of reducing the minimum detectable signal level in this arrangement stems directly from the distinctive properties of amplifiers which use photorefractive crystals. The noise in a photorefractive crystal differs in a fundamental way from the noise in quantum amplifiers in terms of its origin. The noisy factor here consists of photons which are scattered from the pump wave in the direction of the signal wave. The usual reason for the appearance of a noise is a scattering by optical irregularities in the volume of the sample and by defects left by the surface processing. This source of noise can be minimized by technological procedures. The reason for the noise of a fundamental nature is a scattering by thermal fluctuations of the space charge (a scattering by irregularities in the filling of capture centers by charge carriers). In both cases, the noise intensity depends linearly on the intensity of the pump wave.

Another distinctive feature of amplifiers which use photorefractive crystals is that the exponential gain in them remains constant over a wide range of the intensity of the pump wave.[2] For this reason, the noise intensity can be reduced significantly by reducing the intensity of the pump wave. The possibilities for reducing the noise level are restricted by the need to satisfy two conditions. First, the intensity of the pump wave must always remain higher than that of the signal wave. Second, the pump intensity must be high enough to give the amplifier a reasonable speed (the dielectric relaxation time, which determines the relaxation time of the nonlinearity, increases with decreasing light intensity).

Research on the limiting noise characteristics of processes involving a nonlinear frequency-quasidegenerate four-wave mixing constitutes an independent field, in which essentially no work has been done. Further studies should show the absolute limit in terms of the intensity of the input signal which can be achieved by cascading amplifier stages using photorefractive crystals.

In addition to the application which we have described here in a two-beam holographic amplifier, parametric amplifiers could be used for both counterpropagating[5] and copropagating[6] waves. There is the further possibility of an arrangement with a source and a double conjugating mirror[7] with counterpropagating beams of unequal intensity. In the latter arrangement, the signal and pump waves need not be coherent: They can be formed from the output from lasers which are of the same type but independent. Photorefractive crystals can also be used to convert incoherent light from an arbitrary source with a wavelength in the region of photoconductivity of the crystal into coherent light.[8] This possibility suggests an amplification of incoherent optical signals.

In summary, the combining of two principles for light amplification makes it possible to improve the actual noise characteristics of quantum amplifiers.

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