A LASER WITH NONRESONANT FEEDBACK

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A ruby laser with feedback produced by scattering has been investigated. Resonant modes characteristic of lasers with resonant feedback were shown to be absent. It is suggested that nonresonant feedback be used in the design of a stable frequency laser.

1. INTRODUCTION

MASERS and lasers feature a positive feedback achieved by means of resonators.[1,2] Resonators have minimal radiation losses within relatively narrow frequency ranges corresponding to the resonant modes. Consequently, resonant feedback lasers emit a single or several modes which as a rule weakly interact with one another and can be considered as isolated.

Another type of laser is possible, characterized by a nonresonant positive feedback. This means that the photon lifetime in the resonator is independent of the photon frequency. The simplest method of achieving nonresonant feedback consists of substituting a scattering medium for one of the mirrors. The feedback in this case is due to the backward scattering of the emission. The mean emission frequency of a nonresonant feedback laser is determined by the resonance frequency of the active medium, or the maximum-gain frequency, and does not depend on the distance between the scatterer and the mirror. This affords the opportunity to design an optical frequency standard.[3]

The present paper reports on an investigation of a laser with nonresonant feedback produced by scattering. Ruby crystals were used as the active medium, resulting in pulse-type operation. Emission line narrowing from 12 to 0.005 cm^{-1} within a pulse length was established. The time and space characteristics of the emission were investigated. The feasibility of an optical frequency standard based on a nonresonant-feedback laser has been demonstrated.

2. FEEDBACK DUE TO SCATTERING

A laser with a scattering-type feedback consists of an active medium placed between a scatterer and a mirror. The "scatterer–mirror" system replaces the Fabry-Perot resonator of the usual lasers. The electromagnetic field in the laser can be represented, as usual, as a superposition of plane waves propagating in various directions. Every plane wave is scattered and its energy is distributed among the various modes. The scattering of emission in plane waves whose wave vectors lie within the limits of the solid angle of the laser does not cause an energy loss for the laser as a whole. Energy exchange between various modes implies a strong mode interaction. Therefore, the "scatterer–mirror" system has none of the isolated modes present in the Fabry-Perot resonator, and the entire group of interacting scattering-coupled modes should be considered as a whole.

Such a group has a definite attenuation and a corresponding equivalent Q factor

$$Q_\Sigma = \pi \frac{L}{\lambda} \Big/ \ln \frac{1}{r s_\Sigma}, \qquad (1)$$

where L is the mean distance between the mirror and the scatterer, r is the mirror reflection coefficient, and s_Σ is the coefficient of backward scattering into a group of scattering-coupled modes of the same polarization.[1)] This coefficient is determined by the expression,

$$s_\Sigma = \frac{1}{1+\rho} \iint \sigma(\theta, \varphi)\, do = \frac{\alpha}{1+\rho} \begin{cases} \psi_0^{-2}(a/L)^2, & \psi_0 > a/L \\ \approx 1, & \psi_0 < a/L \end{cases}, \qquad (2)$$

where $\sigma(\theta, \varphi)$ is the directivity pattern of backward scattering per pass of a plane wave, ψ_0 is its aperture angle, ρ is the degree of depolarization of the back-scattered light, α is the total coefficient of backward scattering into 2π steradians, and $(a/L)^2$ is the solid angle of the laser (a is the radius of the laser). The threshold gain per pass, k_Σ, for a group of scattering-coupled modes of the same polarization can be determined from the condition $k_\Sigma^2 r s_\Sigma = 1$:

1)We are considering a ruby laser.

$$k_\Sigma = 1/\sqrt{rs_\Sigma}. \tag{3}$$

In the readily obtainable case of $\psi_0 > a/L$,

$$k_\Sigma = \frac{L}{a}\psi_0\left(\frac{1+\rho}{r\alpha}\right)^{1/2}. \tag{3'}$$

It should be noted that the threshold gain of a group of scattering-coupled modes is much lower than the corresponding gain of any single plane wave (the ratio of the threshold gains is $L\lambda/a^2 \ll 1$).

Scattering media with a narrow back-scattering directivity pattern ($\psi_0 < a/L$) may be used to achieve oscillation with a comparatively low gain per pass, $k_\Sigma \approx 1/\sqrt{r\alpha}$. Emission losses in "transmission" of the scatterer (forward scattering) can be eliminated by placing the scatterer in a ring resonator.[2)]

An important feature of the mirror-scatterer system is the absence of resonant discrete modes with frequencies $nc/2L$ (n is an integer) and others. Owing to the interaction of various modes and the associated large losses of each mode, and owing to the absence of a definite scattering boundary (the scattering length is $\gg \lambda$), the spectrum of this system is continuous. Consequently, the output frequency of a laser with scattering feedback is determined by the resonance frequency of the active medium, rather than by the resonator as is the case with conventional lasers.

3. EXPERIMENTAL RESEARCH

The diagram of a laser with scattering feedback is shown in Fig. 1. The active medium consists of two ruby crystals 2 and 3 in tandem, each 24 cm long and 1.8 cm in diameter. To avoid self-excitation, the end faces of the crystals were cut at the Brewster angle. The gain per pass through both crystals reached 10^3. Feedback was achieved by means of mirror 4, having a reflection coefficient $r = 70\%$, and a volume or surface scatterer 1. Sulfur hydrosol in a cell 15 cm long was used as the volume scatterer. The cell window was inclined at the Brewster angle to the laser beam. The sulfur particles were smaller than the wavelength of the emitted light. The surface scatterer was a magnesium oxide film sputtered on the surface of an aluminum plate. The light beam transmitted by mirror 4 and attenuated by filter 5 entered photocell 6, whose signal was recorded by oscilloscope 7.

Figure 2a shows an oscilloscopic trace of the laser output emission for the case of below-threshold pumping, and Figs. 2b and 2c, for the case of above-threshold pumping. Above-threshold pumping resulted in emission fluctuations that are typical for laser oscillation. The oscillation threshold in the given laser was reached, according to (3′), at a gain per pass $k_\Sigma \approx 400$. It was practically independent of the angle of inclination of the scatterer when the angle was varied up to 60°. Increasing the distance between the scatterer and the crystal increased the threshold as predicted by (3′). In the case of feedback based on the volume scatterer, the output emission had regular and attenuating fluctuations (Fig. 2c).

Oscillation in such a laser is described by energy-balance equations and particle-population balance equations, since these equations do not account for the phase relations existing in lasers with resonant feedback. As we know, the solution of the balance equations[5] leads to regular damped fluctuations.

A photocell with a large resolution time (1.0 nsec)[6] and an S1-14 oscilloscope were used

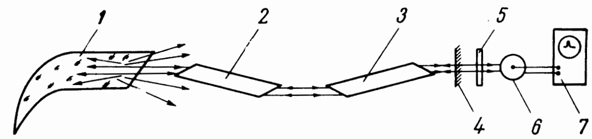

FIG. 1. Experimental setup—laser with scattering feedback.

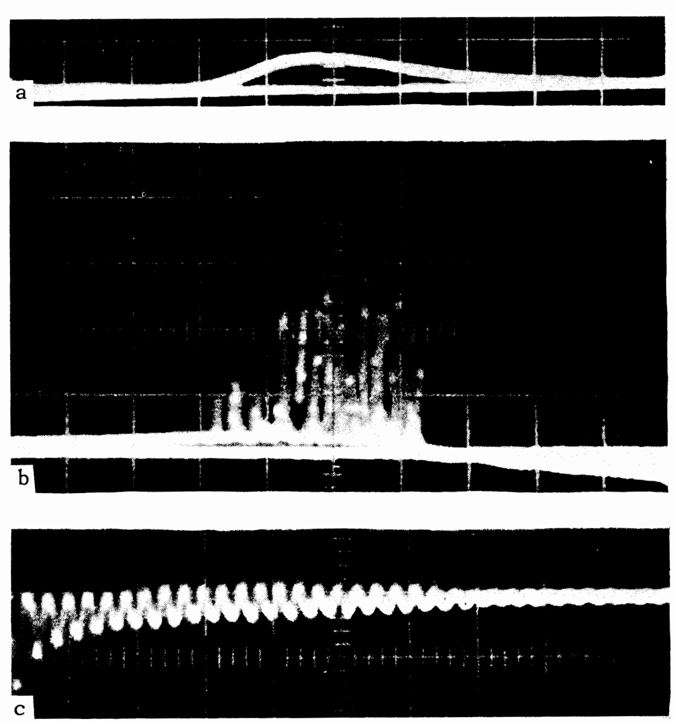

FIG. 2. Oscilloscopic traces of laser emission. (a)—Below-threshold pumping; (b)—above-threshold pumping, surface scatterer; (c)—above-threshold pumping, volume scatterer. Sweep in (a) and (b)—200 microseconds per division; in (c)—10 microseconds per division.

[2)]A ring resonator with an optically inhomogeneous internal plate to "intermix" angular modes was considered in [4].

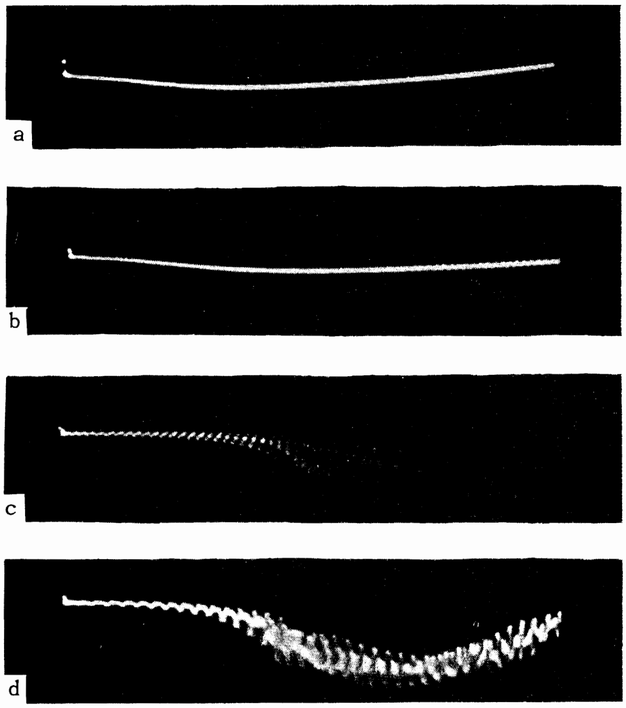

FIG. 3. Oscilloscopic traces of an individual spike. (a)—Volume scatterer; (b)—surface scatterer; (c) and (d)—resonant feedback. Sweep—500 nsec.

to study the time structure of a single emission spike. Figure 3a shows the oscilloscopic trace of laser emission using a volume scatterer, and Fig. 3b the case of a surface scatterer. For the sake of comparison, Figs. 3c and 3d show oscilloscopic traces of the emission of a laser with a Fabry-Perot resonator obtained by replacing the scatterer by a second mirror. The distance between mirrors was 100 cm (Fig. 3c) and 200 cm (Fig. 3d). Traces 3c and 3d show clear beats of neighboring axial modes at the frequency c/2L, where L is the length of the resonator. The amplitude of the beats is much lower when the surface scatterer is used and the beats disappear altogether when the volume scatterer is used. This indicates the absence of resonance at frequencies nc/2L (where n is an integer).

The emission spectrum was obtained with a Fabry-Perot etalon. The interferometric image was time-resolved by a high-speed SFR-2m camera operating at 3×10^4 rpm. The time resolution made it possible to examine the spectrum of an individual spike. Figure 4a shows laser emission spectra obtained with an etalon having a 30 mm plate separation. Figure 4a shows the emission spectrum of a laser with scattering feedback and Fig. 4b shows that of a conventional resonance-feedback laser with a 6% pump excess over threshold. In the first case (feedback with an MgO scatterer) we observed a single emission frequency which smoothly changed from spike to spike be-

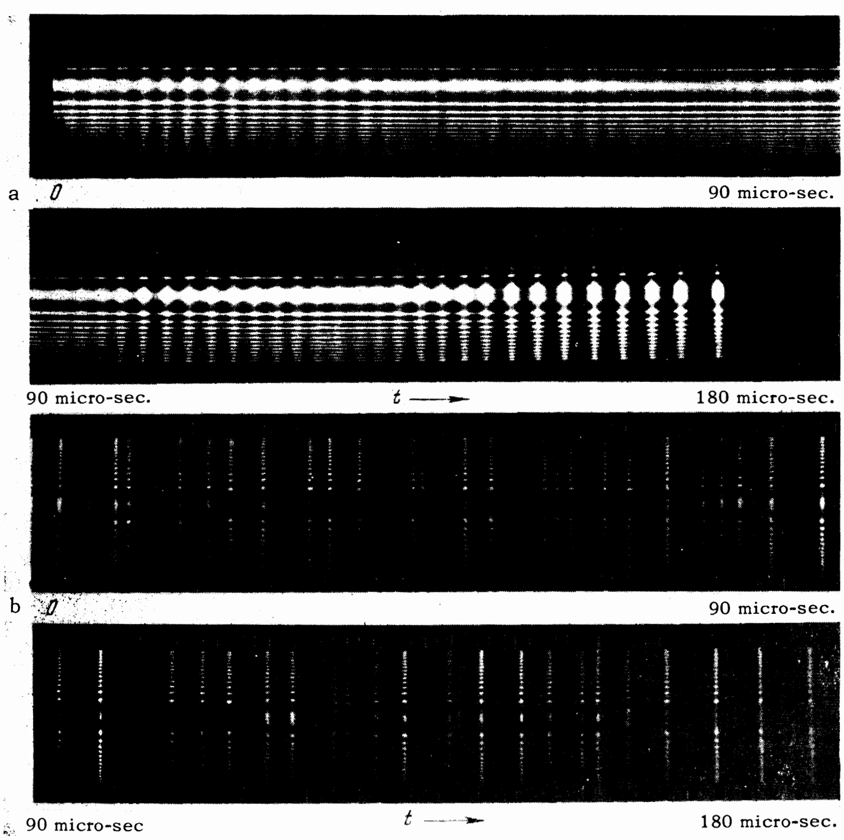

FIG. 4. Interference patterns of laser emission spectrum. (a)—Surface-scattering feedback; (b)—resonant feedback.

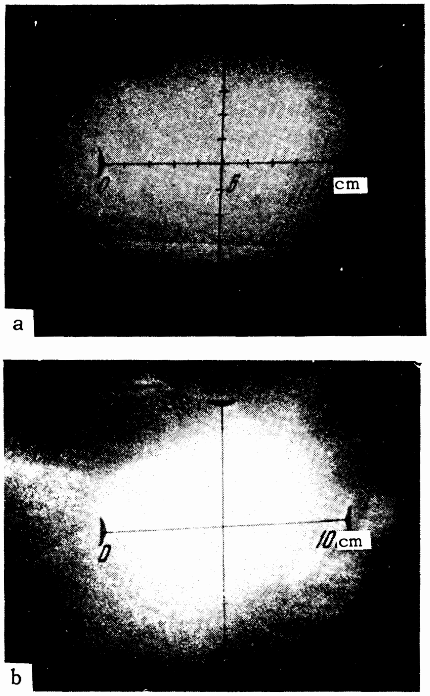

FIG. 5. Intensity distribution of laser emission on the screen. (a)—Scattering feedback; (b)—resonant feedback.

cause of the thermal shift of the ruby luminescence line. In the second case (resonant feedback), a random frequency variation was observed from spike to spike and the emission from individual spikes consisted of several components. In order to obtain a more precise measurement of the emission linewidth, a Fabry-Perot etalon with a 150 mm plate separation was used. According to these measurements, the emission line consists of a single component with a spectral width not exceeding 5×10^{-3} cm^{-1}. The absence of any resonance at the frequencies $nc/2L$ is due to the nonresonant character of the scattering feedback.

The divergence of laser emission was determined by photographing the light intensity distribution on a screen placed 2 m away from the laser output mirror. Figure 5a shows the intensity distribution of a scattering-feedback laser, and Fig. 5b shows an analogous picture for a conventional laser with resonant feedback. It is seen from Fig. 5 that the intensity distribution is more uniform in the scattering-feedback laser than in the resonant-feedback laser. The emission divergence in this case is determined by the angular dimensions a/L of the active medium ($2a$ is the crystal diameter and L is the distance between the mirror and the scatterer), since the angular aperture of the directivity pattern is larger than a/L. Figure 5a shows the rings due to the interference of light at the surfaces of the output mirror. There are no rings

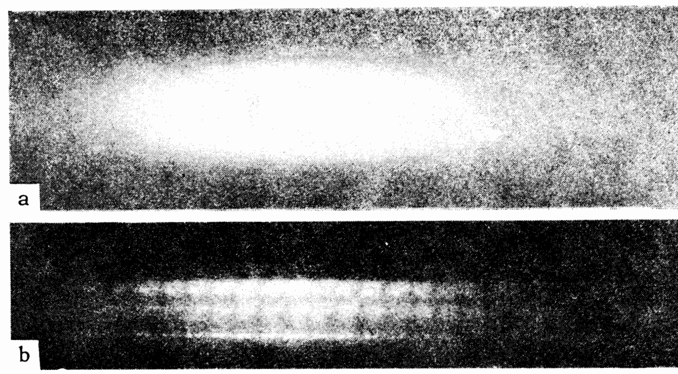

FIG. 6. Diffraction of laser emission by a grating. (a)—scattering feedback; (b)—resonant feedback.

in Fig. 5b, because the emission is less monochromatic in this case.

Spatial coherence of laser emission was studied by observing diffraction in a grating system consisting of several slits. The width of a slit was 0.025 mm and the spacing between slits was 0.25 mm. The grating was placed in the path of the beam at a distance of 25 cm from the output mirror. There was no diffraction pattern in the case of a laser with scattering feedback (Fig. 6a). The diffraction pattern was observed in the far field in the case of the resonant-feedback laser (Fig. 6b). According to this experiment, the length of spatial coherence of the laser emission does not exceed 0.25 mm when scattering feedback is used.

The above experiments indicate that scattering feedback is nonresonant in nature and the resulting emission has two important properties: a high monochromaticity and independence of emission frequency from the "resonator" dimensions.

Experiments were also performed to obtain laser action in systems using other scattering media, including those formed by the action of intense luminescence of the ruby (burning and vaporization of the medium). A typical picture of laser emission obtained in such a case is given in Fig. 7a (black fabric) and Fig. 7b (mylar film coated with aluminum and placed at an angle to the laser axis). It is apparent that the type of laser action depends upon the nature of the scatterer.

The nonresonant feedback laser was Q-switched to increase the power. A Kerr cell was placed between the mirror and the active substance. The length of the resulting emission pulse was about 200 nsec.

4. WIDTH OF THE EMISSION SPECTRUM

In a resonant-feedback laser the line narrowing above threshold is determined by the resonance properties of the resonator; in the nonresonant-

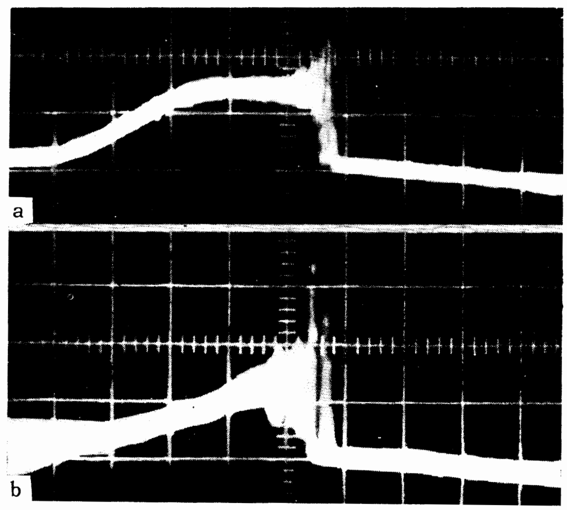

FIG. 7. Oscilloscopic traces of laser emission with scattering feedback due to the action of intense luminescence of ruby. Time flows from right to left.

feedback laser, line narrowing is determined by the resonant properties of the active substance. The emission-line narrowing is due to the fact that photons having the maximum gain frequency ν_0 develop faster than photons of other frequencies. The spectral-narrowing limit attainable in continuous-wave lasers with homogeneous line width is determined by the fluctuations. The main sources of fluctuations are spontaneous emission and fluctuating (Brownian) motion of the scattering particles. The contribution of spontaneous emission to the line width is much larger in nonresonant-feedback lasers than in the resonant-feedback lasers. Basically this is due to the larger solid angle subtended by the wave-vector directions of the laser output. Allowance for the effect of spontaneous emission calls for the study of the statistical properties of the emission from a nonresonant-feedback laser, which apparently are substantially different from those of conventional lasers.

Fluctuating (Brownian) motion of the scattering particles in a liquid causes emission-line broadening due to the Doppler effect in scattering. The mean free path of the scattering particle in a liquid, given typical parameters of the liquid (temperature, viscosity) and of the scattering particles (radius, density), regarded as spherical, is much less than the wavelength of the laser emission. Consequently, the Doppler broadening of the emission line will be determined by the diffusion of the particles.[7,8] In this case, the laser emission line width is determined by the expression

$$\Delta\nu = kT / \lambda^2 a\eta, \tag{4}$$

where T and η are the temperature and viscosity, respectively, of the liquid, and a is the radius of the scattering particles. For the typical values $T = 300°$ K, $\lambda = 0.7 \times 10^{-4}$ cm, $a = 10^{-5}$ cm, and $\eta = 10^{-2}$ poise, we have $\Delta\nu \sim 1$ cps. It should be noted that the macroscopic motion of the scattering particles due to currents and other effects in the liquid may further increase the line width and cause a shift in the emission spectrum. Therefore it is recommended to use viscous liquids and even solid volume scatterers in the feedback systems.

To obtain continuous-wave laser action with nonresonant feedback, one can use active materials consisting of gaseous mixtures (Xe or Ne with He, etc.), having transitions with a high gain per pass. In such a case it will be possible to obtain emission lines with a narrow spectrum, where the line width does not depend upon the geometry of the resonator. Such lasers may then become the basis for the design of optical frequency standards.

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