In conclusion, it should be indicated that continuous emission in the region of the vacuum ultraviolet should be observed when solid targets are bombarded by a beam of helium ions. This emission will arise when the excited $He_2$ molecules go over to the unstable ground state.


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## THREE-LEVEL GAS LASER [1)]


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1. We describe here a gas laser in which the gain necessary for lasing is produced by external radiation from another laser. We investigated the pair of transitions $3s_2 - 2p_4$ ($\lambda_1 = 0.63\ \mu$) and $2s_2 - 2p_4$ ($\lambda_2 = 1.15\ \mu$) of neon (Fig. 1). An external field at $\lambda = 0.63\ \mu$, resonant with one of the two neighboring transitions $3s_2 - 2p_4$, produces a dip in the velocity distribution of the atoms at the common level $2p_4$ (the Bennett hole [1]). As a result, the gain line at the $2s_2 - 2p_4$ transition represents a narrow Lorentzian peak. It is important that this peak is produced by atoms whose velocity projections on the direction of propagation of the external field lie in the narrow interval $\Delta v \approx (\gamma_{3s_2} + \gamma_{2p_4})/k_1$, where $\gamma$ is the level width and $k_1$ the wave number. The spectral characteristics of the laser at $\lambda = 1.15\ \mu$ differ greatly in this case from those observed so far in gas lasers, since the lasing at $\lambda = 1.15\ \mu$ is realized, as it were, by an atomic beam. However, the complete analogy with the atomic beam is limited by the nonlinear effects of the interaction of the resonant fields in the quantum system [2-5], which lead to a change in the line shapes of the emission and absorption of the weak field in the presence of the strong one. For moving atoms, this interaction causes the shapes of the emission and absorption lines of the $2s_2 - 2p_4$ transition to become dependent on the direction of the field propagation (nonlinear

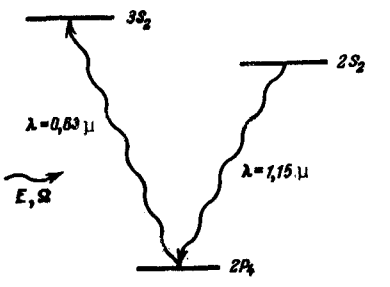

Fig. 1. Working-level scheme

[1)] Reported at the All-union Symposium on Nonlinear Optics, Kiev, October 1968.

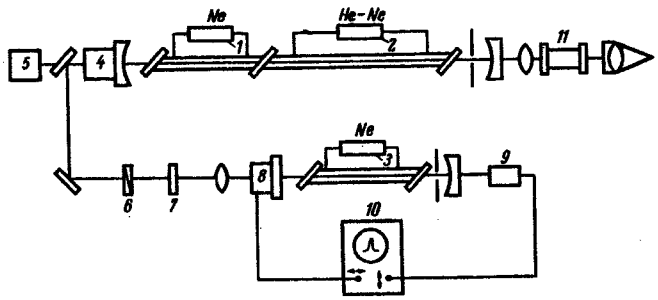


Fig. 2. Diagram of experimental setup: 1,2,3 - power supply, 4,8 - piezoceramics, 5 - photocell, 6 - polaroid, 7 - quarter-wave plate, 9 - ir receiver, 10 - oscilloscope, 11 - Fabry-Perot interferometer.

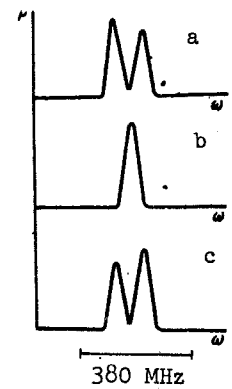


Fig. 3. Oscillogram of laser power ($\lambda = 1.15\ \mu$) vs. frequency at different deviations $\Omega$ of the $0.63\ \mu$ laser frequency: a - $\Omega < 0$, b - $\Omega \approx 0$, c - $\Omega > 0$.

interference effects) [6].

2. The beam from a tunable single-mode He-Ne laser at wavelength $\lambda = 0.63\ \mu$ and power ~15 MW [1)] passed through discharge tube 3 filled with pure Ne, which simultaneously served as the active medium of the $\lambda = 1.15\ \mu$ laser (Fig. 2). The experiments described here were made at neon pressures 0.3 - 0.5 mm Hg. Under these conditions absorption at the transition $3s_2 - 2p_4$ was always observed, and the lasing at $\lambda = 1.15\ \mu$ was produced only in the presence of an external field. The experiment consisted of scanning the frequency of the $1.15\ \mu$ laser at fixed deviations $\Omega$ of the frequency of the $0.63\ \mu$ laser from the center of the absorption line. At $\Omega = 0$, the lasing at $1.15\ \mu$ was observed near the center of the line in the form of one peak (Fig. 3b). When the gain exceeded threshold by a factor of 2, the width of the interval in which the lasing took place was 75 ± 10 MHz. At $\Omega \neq 0$, the peak of the $\lambda = 1.15\ \mu$ generation doubled, and the power curve of the lasing at $\lambda = 1.15\ \mu$ as a function of the frequency deviation $\Omega'$ from the center of the line was asymmetrical; the sign of the asymmetry was determined by the sign of the deviation $\Omega$ (Figs. 3a and 3b).

3. The observed curves (Fig. 3) can be explained using the notion of the Bennett hole with allowance for the nonlinear interference effect. The gain at $\lambda = 1.15\ \mu$ in the standing-wave field can be regarded as the sum of the gains of two waves traveling in opposite directions. When one of the traveling waves is resonant with the atoms having a velocity in the region of the Bennett hole, the gain is maximal. Therefore, when $\Omega \neq 0$, one Bennett hole at the level $2p_4$ gives two peaks on the gain curve for the $2s_2 - 2p_4$ transition at distances $\Omega'_{1,2} = \pm(k_2/k_1)\Omega$ from the center of the line. As shown in [6], for the $2s_2 - 2p_4$ transition the influence of the strong field at $\lambda = 0.63\ \mu$ on the absorption probability is $k_2\bar{v}/\Gamma_2$ times stronger than on the stimulated-emission probability ($k_2\bar{v}$ and $\Gamma_2$ are the Doppler and Lorentz widths of the $2s_2 - 2p_4$ transition). Taking this into account, we can obtain from [6] the gain of the $1.15\ \mu$ line, as the difference between the stimulated emission from the $2s_2$ level and the absorption at the $2p_4$ level:

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1) Selection was ensured by an absorbing cell with Ne in accordance with [7]. The power and mode composition were monitored by photocell 5 and Fabry-Perot interferometer 11 (Fig. 2).

$$G_{1,15} = e^{-(\Omega'/k_2\bar{v})^2}\left\{G_0 + T_0\frac{{}_{1,15}|pE|^2}{A_{0,63}\hbar^2\gamma_{3s_2}\gamma_{2p}}\left(\frac{k_2}{k_1}\right)^2\gamma_{3s_2}\times\right.$$

$$\left.\times\left[\frac{\Gamma_+}{(\Omega'-\frac{k_2}{k_1}\Omega)^2+\Gamma_+^2}+\frac{\Gamma_-}{(\Omega'+\frac{k_2}{k_1}\Omega)^2+\Gamma_-^2}\right]\right\}, \tag{1}$$

where $G_0$ is the unsaturated gain or absorption at the center of the 1.15 μ line, $T_0$ the unsaturated absorption at the center of the 0.63 μ line, A the spontaneous-transition probability, E the field amplitude at λ = 0.63 μ, p the matrix element of the dipole moment of the $3s_2$ - $2p_4$ transition, and $\Gamma_-$ and $\Gamma_+$ the widths of the peaks for waves of different directions, equal to:

$$\Gamma_- = \gamma_{2s_2} + \gamma_{2p_4} + \frac{k_2}{k_1}(\gamma_{3s_2} + \gamma_{2p_4}) \qquad k_2k_1 < 0,$$

$$\Gamma_+ = \gamma_{2s_2} + \gamma_{2p_4} + \frac{k_2}{k_1}(\gamma_{3s_2} + \gamma_{2p_4}) \qquad k_2k_1 > 0. \tag{2}$$

It is seen from (1) and (2) that the 1.15 μ wave propagating in the same direction as the 0.63 μ wave experiences a larger gain at the maximum than the wave traveling in the opposite direction, although both interact with the same group of atoms. Therefore, the generation condition will be satisfied for the deviation $\Omega_1' = (k_2/k_1)\Omega$ earlier than for $\Omega_2' = (k_2/k_1)\Omega$. In the case of lasing at 1.15 μ, the generation power will depend on the character of the saturation of the $2s_2$ - $2p_4$ transition, which is not considered in the theory [6]. However, at a small excess over threshold, we can expect the generation line shape to reflect the spectral dependence of the gain (1). Therefore two peaks appear on the plot of the 1.15 μ power against the frequency, and in the case of a sufficiently large deviation Ω, each peak corresponds to the gain of a wave traveling only in one direction. The difference in gain for waves traveling in opposite directions, resulting from the interference effects, becomes manifest in the generation power at the two peaks corresponding to the frequency deviations $\Omega_1' = (k_2/k_1)\Omega$ and $\Omega_2' = -(k_2/k_1)\Omega$. All these conclusions agree with the experimentally observed asymmetry of the generation line shape at 1.15 μ. We note that the dependence of the line shape of spontaneous emission from an He-Ne laser on the observation direction, recently observed by H. Holt [7], has apparently the same physical nature. Our experiment has shown that nonlinear interference effects can greatly change the gain line shape and the generation conditions in a three-level gas laser. At a definite choice of the transitions, it is possible to "eliminate" practically completely the motion of the atoms and to obtain a gain line having unusual spectral properties (with a width smaller than the natural width at the given transition [6]) in one of the directions. Experiments on ring lasers are of interest in this connection.

In conclusion we note that a three-level laser, together with other direct methods of

observing Bennett holes, say in spontaneous emission, can be successfully used to determine the radiative and collision widths, to investigate the performance of a laser in a magnetic field, and also to stabilize the frequency of a powerful gas laser. The use of molecular systems pumped by chromatic radiation in accordance with a three-level scheme will apparently permit amplification at new wavelengths with supernarrow lines.

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# E R R A T U M

Article by I. M. Beterov and V. P. Chebotaev, Vol. 9, No. 4

On p. 219, the second formula of (2) reads "...($\gamma_{3s_2} + \gamma_{2p_4}$)..." should read ($\gamma_{3s_2} - \gamma_{2p_4}$).." On the same page, line 8 from the bottom reads " H. Holt [7],..." should read "H. Holt [8],..." and on the third line from the bottom reads "...transition [6]..." should read "transition [7]." The following additional reference should be added: [8], H. K. Holt, Phys. Rev. Lett. 20, 410 (1968)].