Narrowband operation of a pulsed dye laser without intracavity beam expansion

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A new simple cavity design for nitrogen-laser-pumped dye lasers is presented. Narrowband operation is achieved with a single dispersive element and without any intracavity beam expansion. The dispersive element is a diffraction grating used near grazing incidence with an additional mirror, instead of the usual Littrow arrangement. The large angular dispersion obtained results in a linewidth of 0.08 cm^{-1}. The typical peak power obtained is 4 kW with 50 kW in the pump beam. Calculations of linewidth based on single-pass estimates are presented and are found to be in good agreement with experimental results.

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Nitrogen-laser-pumped dye lasers have been extensively used in the last few years. The most successful cavity design for such lasers was that reported first by Hänsch.[1] In this design, spectral narrowing and tuning are achieved by the use of a diffraction grating in a Littrow mounting. The wavelength selectivity is improved by using an intracavity beam expander which may be a lens telescope,[1] a prism,[2] or a mirror telescope.[3]

The angular dispersion of a diffraction grating in a Littrow mount is given by[4]

$$\frac{d\theta}{d\lambda}=\frac{m}{a\cos\theta}=\frac{2\tan\theta}{\lambda}, \qquad (1)$$

where m is the diffraction order, a is the groove spacing of the grating, and θ is the angle of the diffracted beam. In a nitrogen-laser-pumped dye laser the excitation time is of the order of 10 nsec, so that only a few light passes in the cavity are possible. As a result, the linewidth of the dye laser is not much narrower than the single-pass bandwidth of the cavity (full width) given by[2]

$$\delta\lambda=\frac{2\delta\alpha}{(d\theta/d\lambda)}, \qquad (2)$$

where $\delta\alpha$ is the half angle divergence of the superfluorescent beam incident on the grating. The usual way to reduce the spectral bandwidth $\delta\lambda$ is to use a highly dispersive grating at a high angle of incidence (60°–75°), and at the same time reduce the divergence $\delta\alpha$ by expanding the superfluorescent beam inside the cavity.[1,2]

The linewidths obtained with this technique and without using intracavity etalons were 0.1–0.2 cm^{-1} with a prism expander[2] and somewhat less with a lens telescope.[1] By using a mirror telescope a much larger linewidth (1.5 cm^{-1}) was obtained with nitrogen-laser pumping[3] because a much longer cavity was used. In the following we show that a linewidth of 0.08 cm^{-1} is obtainable without expanding the beam in the cavity. This is achieved by mounting the grating in the cavity near grazing incidence, thereby increasing its angular dispersion to the maximum. In other words, instead of reducing the numerator in Eq. (2) by beam expansion, we propose to increase the denominator by increasing the angle of incidence on the grating.

The use of gratings at angles of incidence approaching grazing is known in x-ray spectroscopy.[5] This unusual arrangement is thought to be impractical for frequency narrowing and tuning of lasers because it is accompanied by high reflection losses. The diffraction efficiency at angles of incidence much higher than 75° is indeed very low. However, in a high-gain laser, efficient lasing is possible with the following arrangement:

(1) A 100% mirror is placed at the opposite end of the cavity, replacing the quartz window in Hänsch's design. The reflection from the grating (zeroth order of diffraction) is used to couple out the energy.

(2) The cavity is kept as short as possible so that several light passes in it are possible during the short excitation time. In this way, even a very small amount of feedback from the grating is sufficient to stimulate emission at the desired wavelength.

There are still two serious problems caused by the use of a diffraction grating in a Littrow arrangement near grazing incidence, they are as follows:

(1) Diffraction gratings blazed for such an unusual angle of incidence are not available commercially.

(2) When rotating the grating for tuning purposes, not only the wavelength is changed, but also the linewidth, which is strongly dependent on θ [Eqs. (1) and (2)]. The direction of the output beam also changes with rotation.

These difficulties are easily overcome by using a non-Littrow arrangement with an additional mirror as shown in Fig. 1. In this arrangement a small part of the beam

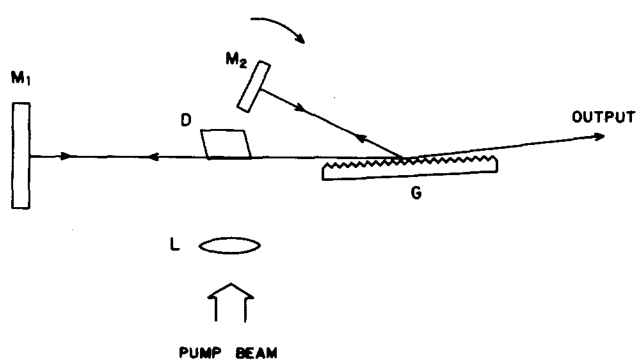

FIG. 1. The dye laser cavity: M_1, fixed 100% mirror; M_2, rotatable mirror; D, dye cell; L, cylindrical lens; G, diffraction grating.

incident on the grating is diffracted, the larger part being reflected out. This diffracted beam is reflected by mirror M_2. Due to the angular dispersion of the diffracted beam, only a small wavelength range is reflected back along the direction of incidence on mirror M_2, the wavelength depending on the mirror orientation. This back-reflected beam is diffracted again by the grating and is returned to the dye cell. The zeroth order of this second diffraction is reflected out and is lost.

Such a combination of a diffraction grating and a plane mirror has already been used in spectrographs for the purpose of increasing resolving power and dispersion.[6] The angular dispersion thus obtained is[6]

$$\frac{d\theta}{d\lambda}=\frac{2m}{a\cos\theta}. \tag{3}$$

It is twice as large as that obtained in the usual Littrow arrangement under the same conditions (assuming a, m, and θ are constant). This increase in dispersion is due to the fact that the beam is diffracted twice before returning to the dye cell. When the illumination is near grazing incidence, the whole width of the grating may be illuminated. In this way the highest resolution obtainable with the grating is achieved, as all grooves are illuminated.[4]

With the angular dispersion given by Eq. (3), the single-pass bandwidth of the cavity becomes, according to Eq. (2),

$$\delta\lambda=\frac{a\cos\theta}{m}\delta\alpha. \tag{4}$$

As mentioned above, the linewidth of the output beam is expected to be somewhat smaller than this. To obtain a narrow bandwidth $\delta\lambda$, a highly dispersive grating should be used (which dictates a small value of a/m) and the angle θ should be as high as possible. θ is only limited by the grating width; thus, the grating should be large enough to intercept the beam completely at the desired angle of incidence.

The grating used in the present experiment was a 15-cm-wide echelle grating with 316 lines/mm, blazed at 63°26′. It was used in the strongest diffraction order at grazing incidence. It should be noted that the strongest order in the present arrangement is not necessarily that which is strongest in a Littrow arrangement. With Rhodamine 6G in hexafluoro-isopropanol (2.5×10^{-3} M) the dye laser was operated near 5700 Å in the ninth order of the echelle, while in the Littrow arrangement the tenth order would have been indicated.

Since a grating with many diffraction orders was used, it was necessary to tilt it a little to prevent unwanted direct feedback from it to the dye cell. Such an undesirable direct feedback may occur when the equation for the Littrow arrangement ($2a\sin\theta=m\lambda$) is satisfied for an order higher than the one used. Therefore, the grating should be mounted so that its grooves are not perpendicular to the plane of incidence, but at the same time they must be perpendicular to the line illuminated on the grating by the incident beam. If a grating with a groove spacing satisfying $\frac{1}{2}\lambda < a < \lambda$ is used in first order, only a single diffraction order exists so that such a tilt is not necessary.

Another disadvantage of the high-order echelle compared with a first-order grating is that a superposition of different orders at slightly different wavelengths is possible in the present arrangement.[6] The beam, diffracted twice in the ninth order before returning to the dye cell, may be overlapped by beams diffracted at other combinations of orders, such as $(8+10)$ or $(10+8)$. If this happens, the spectrum of the output beam will contain several narrow lines. Such a superposition was prevented in the present experiment by using a small mirror, M_2, and by mounting it far enough from the grating,[6] so that only a single order reached mirror M_2.

The mirrors used were aluminum coated with a reflectivity of about 90%. The cavity length was 25 cm when measured to the middle of the echelle. The nitrogen laser used for pumping was a homemade longitudinally excited laser operating at a repetition rate of 10 pps with 50 kW peak power and a pulse duration of 12 nsec (FWHM).

The superfluorescent beam incident on the grating was diffraction limited, due to the large distance (45 mm) between mirror M_1 and the dye cell.[1] The far-field divergence of this beam was measured and was found to be 2.3 mrad (half-angle). The large width of the echelle made it possible to operate at an angle of incidence as high as 89°30′. At this angle, the calculated angular dispersion [Eq. (3)] was 65 mrad/Å and the corresponding single-pass bandwidth [Eq. (4)] was 0.07 Å.

The typical peak power obtained with Rhodamine 6G was 4 kW in pulses of 4 nsec (FWHM). The linewidth was measured by photographing the fringes of a Fabry-Pérot interferometer with a free spectral range of 0.5 cm^{-1} and was found to be 0.08 cm^{-1} or a little less than 0.03 Å (near 5700 Å). The measured half-angle divergence of the output beam was 1 mrad. A tuning range of about 400 Å was obtained by rotating mirror M_2. The measured linewidth and divergence of the output beam were found, as expected, to be smaller than the single-pass values ($\delta\lambda=0.07$ Å; $\delta\alpha=2.3$ mrad). This indicated that several round trips were carried out in the cavity during excitation time by virtue of the short cavity. The shortness of the cavity was also responsible for the wide tuning range obtained despite the small amount of feedback from the grating.

The linewidth, lasing efficiency, tuning range, and beam divergence obtained with the cavity design described above were found comparable to those obtained with an intracavity beam expander.[1,2] Moreover, the present arrangement has some obvious advantages compared to the use of an intracavity beam expander; they are as follows:

(1) The cavity does not contain any glass components except the dye cell, so that the laser is much less sensitive to temperature changes and is less vulnerable to high-power beams.

(2) The number of reflecting surfaces in the cavity is small, so that losses caused by undesirable reflections are reduced.

(3) The cavity alignment is very easy and no focusing is required.

As already mentioned, the use of a grating in first order is to be preferred; the only reason for using a high-order echelle was that this was the largest grating available in our laboratory.

Finally, it should be noted that the arrangement described here is, in principle, applicable not only to dye lasers but to any other high-gain laser, the only limitation being the small amount of feedback from the grating.

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Construction and parameter description of a nitrogen laser

A simple N_2 laser has been constructed. Output power of 0.5 MW and about 5 ns FWHM pulse duration has been obtained. The dependences of the peak power energy and duration of the laser pulse on the tension of the power supply nitrogen pressure, and repetition rate were measured. The distribution of radiation intensity in a cross-section of the laser beam was also studied in relation to the repetition frequency of the laser.

In 1963 HEARD [1] obtained a laser action by means of fast electrical discharge in nitrogen. The radiation spectrum of this type laser is complicated; it consists of approximately 30 lines in the ultraviolet region. Over 99% of the energy is emitted in the form of radiation of the wavelength 3371 Å, corresponding to the transition from the $C^3\pi_u$ to $B^3\pi_g$ states in the nitrogen molecule [2].

A necessary condition for obtaining population inversion of the N_2 molecule is a short risetime of electrical discharge in the gas, because the lifetime of the $C^3\pi_g$ state is about 40 ns [3].

We feel that of many possible variants of a medium power nitrogen laser that, described in the present paper, can be most easily constructed under laboratory conditions. It consists of a circuit in which energy is transmitted indirectly by means of an artificial delay line as proposed by SCHENK and METCALF [4]. Electrical circuit of this laser is shown in fig. 1.

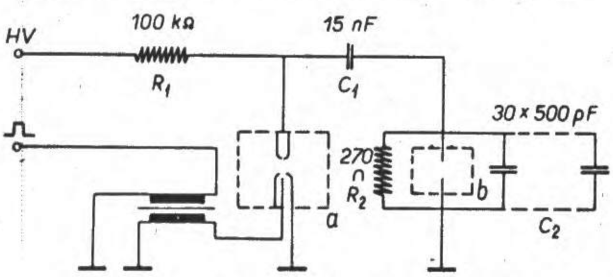

Fig. 1. Electrical circuit of the nitrogen laser

After high voltage is switched on capactitor C_1 is charged trough the resistances R_1 and R_2 to the power supply voltage. The resistance R_2, being low, the voltage in capacitor C_2 and in discharge channel during charging process is low and not sufficient for breakdown. When the spark gap is switched on, the positive electrode of capacitor C_1 becomes earthed, and the capacitor C_2 is charged with the negative tension pulse which appears on the second electrode of capacitor C_1 (the spark gap switch time is much shorter than the discharge time of capacitor C_1).

The charging of capacitor C_2 ends with the breakdown in the discharge channel. After breakdown the battery of capacitors C_2 discharges rapidly in a circuit consisting of capacitors C_2 and the discharge channel. (The influence of resistance R_2 may be omitted because of the negligible resistance of the ionized discharge channel.)

Since the dispersed inductivities of this circuit are low, the switch time of the spark gap (or thyratron) need not be so short as in other types of lasers [5, 6].

The current risetime in the channel and its peak intensity — and thereby the power of the laser — is a complicated function of channel pressure, power supply tension and spark gap switch time, because of the nonlinear resistance of the channel and gap.

Fig. 2 presents a cross-section of the laser discharge channel. Nitrogen is supplied in the region of the windows of the laser and evacuated in the middle part of the channel. Such an arrangement prevents contamination of the laser windows. The glass plates forming the discharge channel were mechanically reinforced by a polyester laminate. The distance between the channel electrodes is 2.1 cm. Because of radio noise arising during laser action an additional internal screen has been installed.

Chemical actionmetric methods were used to measure the energy of the laser pulse [7, 8].

A 25 ml flask containing a 0.0006 M solution of $K_3Fe(C_2O_4)_3$ was exposed to laser pulses. After addition of complexing agents, absorption of the irradiated solution was examined spectrophotometrically at $\lambda = 5100$ Å. This allowed to determine in actionometric solution the concentration of Fe^{++} ions resulting from the irradiation, and the absolute number of photons absorbed by the solution.

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Actionmetric measurements of the laser pulse energy were carried out at a tension of 20 kV, pressure 40 Tr, and frequency 33 Hz. The measured energy

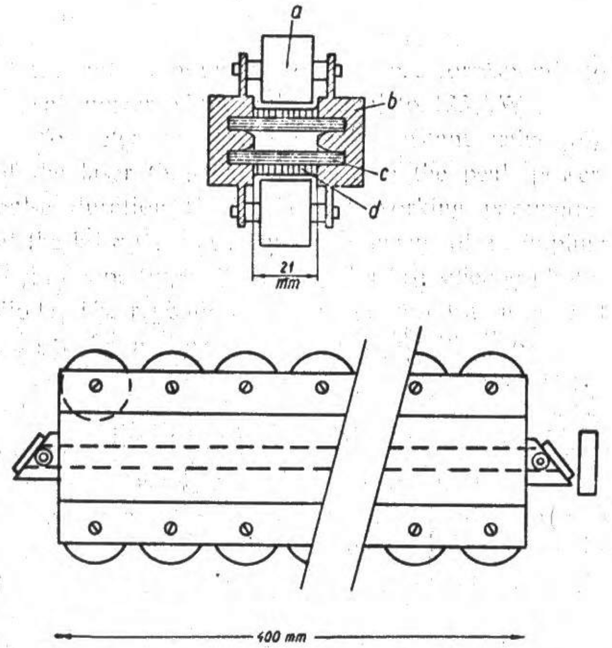

Fig. 2. Cross-section of the laser discharge channel:
a — capacitor 500 pF/25 kV, b — aluminium electrode, c — glass plate, d — polyester laminate

of the pulse amounting to 0.75 mJ, corresponds to a peak power of the pulse, equal to 125 kW.

To determine the optimal constant value E/p of the laser the relations between the peak power, pulse duration (FWHM) and working parametres of the laser were determined by means of a sampling oscilloscope (type OS 150), and a fast silicone photodiode. The repetition rate of the laser was measured with a digital frequency meter (type PFL 16).

Similar relations for another arrangement of the laser (with strip line and travelling wave) were studied in paper [9].

Our measurements were conducted for a laser without mirrors, or with one mirror, and for a laser with a resonator. A quartz plate inserted in front of the laser window served as a second mirror in the resonator.

Constant peak power lines of the pulse, as a function of the power supply tension and nitrogen pressure, are presented in fig. 3a, b, c: (a) laser without mirrors, (b) laser with one mirror, and (c) laser with a resonator. In case (b), the laser works within a much broader range of pressures and at lower tensions than in case (a). In case (c) the power is much higher, the optimum occurring at lower tensions; in this case the range of pressures within which the laser functions efficiently is the broadest one.

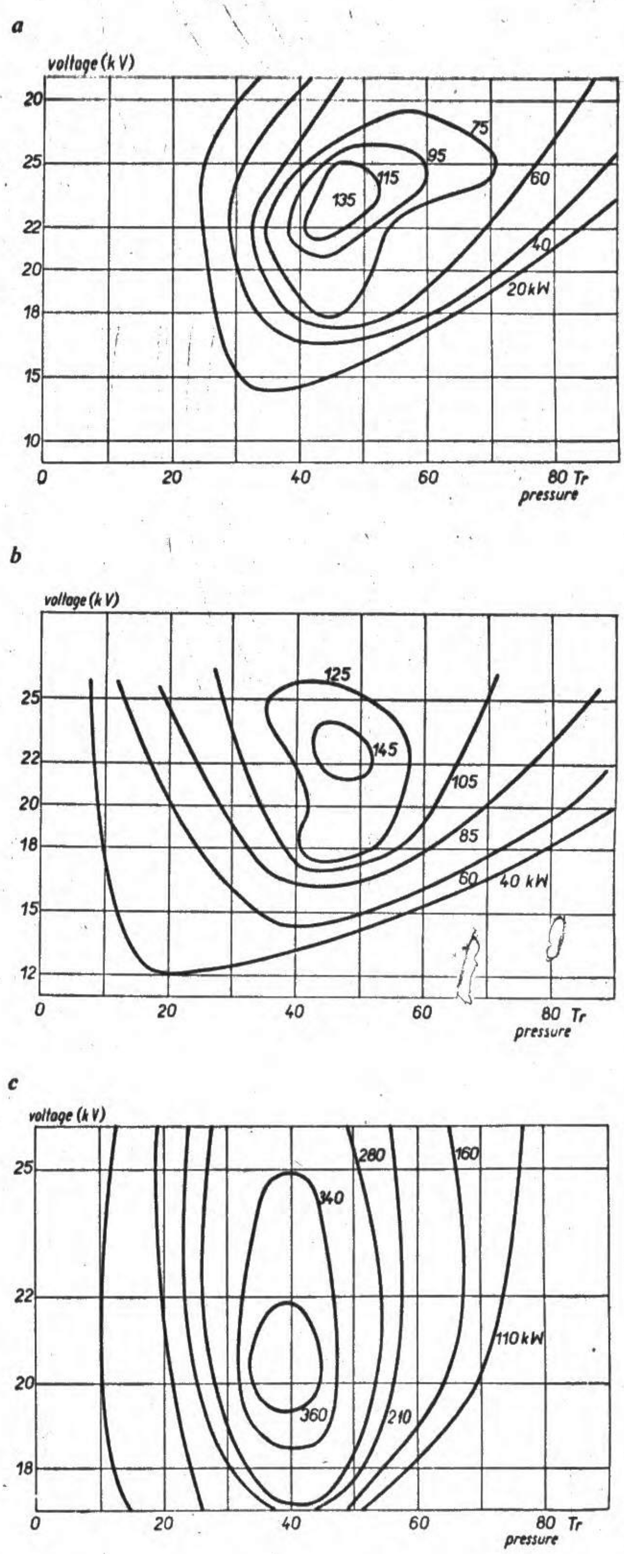

Fig. 3. Laser peak power vs. the power supply tension nitrogen pressure:
a — laser without mirrors, b — laser with one full-reflectivity mirror, c — laser with a resonator (full reflectivity mirror and a quartz plate)

Fig. 4 (a, b) presents lines of the constant energy of the pulse as a function of the power supply tension and nitrogen pressure (a — laser with mirror, b —with resonator). In case (b) a 2.5-fold increase in energy impulse occurs under optimal conditions.

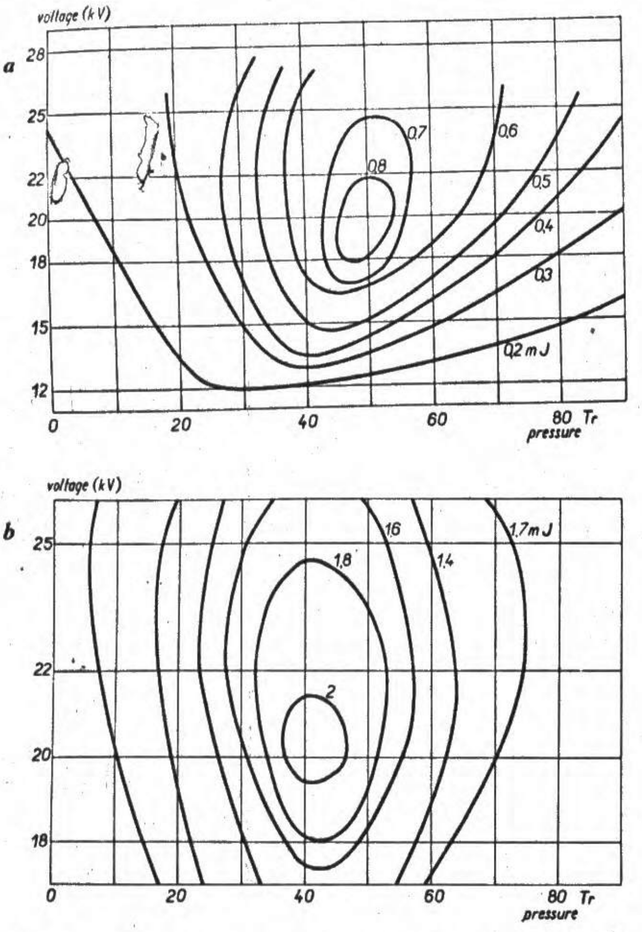

Fig. 4. Laser pulse energy vs. the power supply tension and nitrogen pressure:

a — laser with one mirror, b — laser with resonator

Fig. 5 (a, b) presents the dependence of laser power on the repetition rate at various power supply tensions. Case (a) refers to the laser without mirrors, case (b) to the laser with a single mirror. It appears that for the laser with one mirror the peak power is higher, especially at low tensions and high frequencies. At 18 kV and a frequency 40 Hz, the power increases three-fold due to the addition of one mirror.

Fig. 6 (a, b) presents the dependence of the pulse duration on pressure at various power supply tensions (a — laser with mirror, b — with resonator). The pulse duration (FWHM) increases with the pressure, it decreases as the tension increases, and is not influenced by the presence of either the resonator or single mirror. The pulse duration increases as the nitrogen pressure increases, in contrast with other types of lasers described in the literature (e.g. [10]). The laser pulse duration does not depend on the repetition frequency.

The optimal conditions for laser work at a 33 Hz repetition frequency are: nitrogen pressure 47 Tr, and power supply tension 23 kV. Under optimal conditions the laser constant — the ratio of the tension between channel electrodes to nitrogen pressure and the distance between electrodes — is equal to 120 V/cm·Tr.

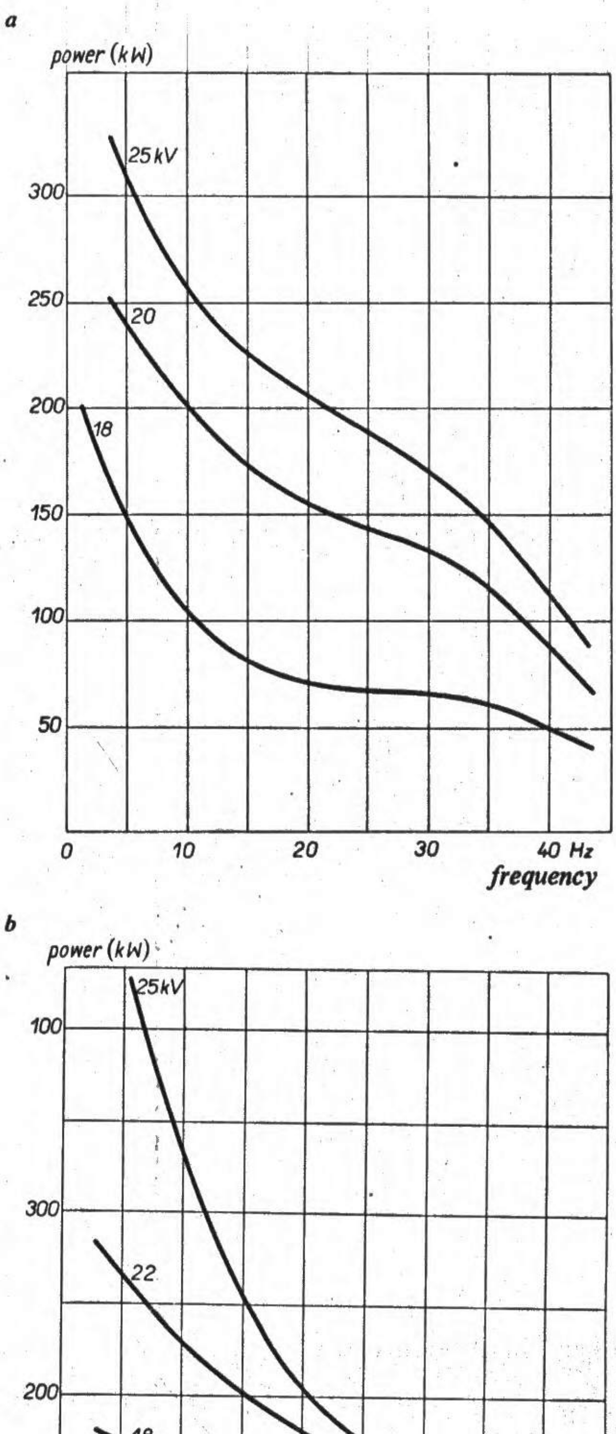

Fig. 5. Laser power vs. the laser repetition rate at various power supply tensions:

a — laser without mirrors, b — laser with one mirror

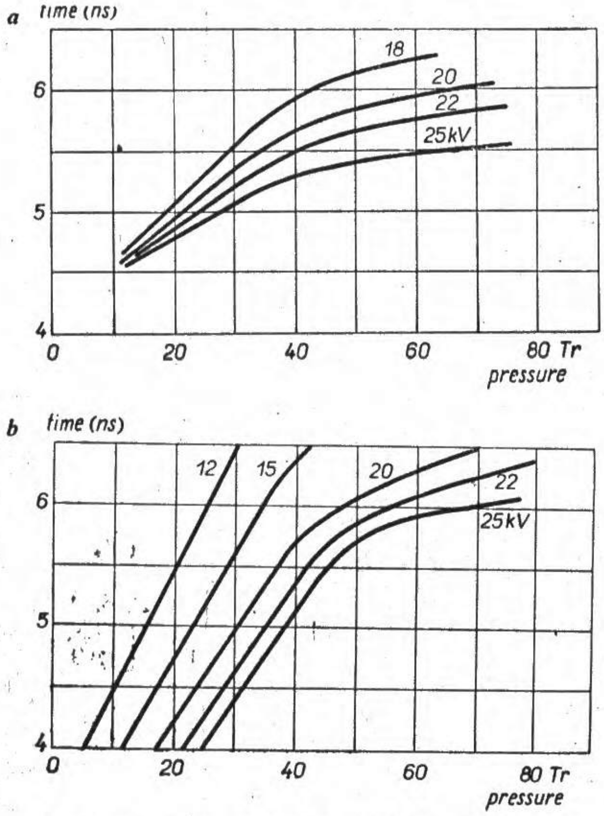

Fig. 6. Laser pulse duration (FWHM) vs. the nitrogen pressure at various power supply tensions:

a — laser with one mirror, b — laser with resonator

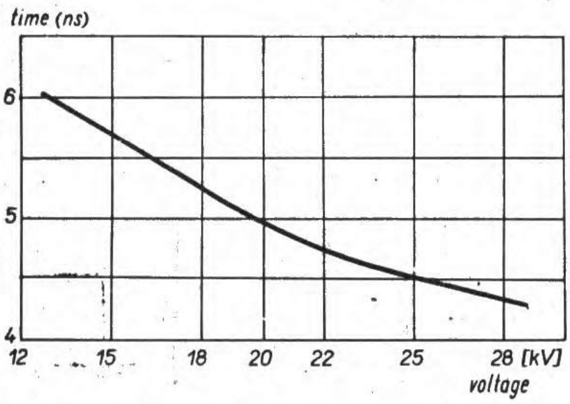

Fig. 7. Laser pulse duration vs. the power supply tension

The nitrogen laser beam is highly divergent. Since often only a part of the surface illuminated by the laser is to be utilized the distribution of radiation intensity in a cross-section of the beam must be known.

Studies of the beam were carried out in the following way: laser radiation was transmitted through a lens onto photographic paper. The distance of the lens from the window was chosen to obtain on the paper an image of the beam cross-section at the exit of the laser channel. The intensity of the radiation was regulated with the aid of two linear polarizers. The distribution of radiation intensity in the beam was studied in relation to the frequency of laser function.

The results obtained are presented in fig. 8. For low repetition frequencies the discharge in the channel is dispersed on the glass walls. Thus these parts of the channel radiate most intensely. For high repeti-

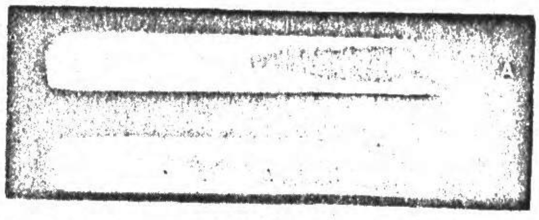

Fig. 8. Cross-section of the laser beam at the exit of the channel:

a — low repetition rate of the laser, b — high (>15 Hz) repetition rate of the laser

tion frequencies the light is almost homogeneous but distributed within the cross-section of the channel.

The construction of nitrogen laser is simple. The laser uses an inexpensive and easily available gas, it works at room temperature and yields easily repeatable pulses. It is a good pumping source for dye lasers working from ultraviolet up to near infrared. In many other applications, short pulse, high repetition frequency, and relatively high power are useful.

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Описание конструкции и параметров азотного лазера

В работе описан сконструированный простой лазер N_2. Полученная выходная мощность составляет 0,5 МВт, а продолжительность импульса FWHM — около 5 нс. Измерена зависимость пиковой мощности и продолжительность импульса лазера от напряжения питателя мощности, давления азота и частоты повторения импульса. Распределение плотности излучения в сечении лазерного пучка исследовалось в отнесении к частоте повторения импульса лазера.

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