ultraviolet harmonics of the emission of ruby and neodymium lasers) in organic compounds and generation with such compounds.

2. This method was used to solve practically completely the problem of filling the visible band. The active processes used in this case are organic dyes[1]. In the UV region, however, the use of dyes is impossible, since organic compounds suitable for the generation in this band should have the following basic properties:

a) intense absorption in the UV band (the extinction coefficient should amount to tens of thousands of l/mole-cm);

b) large fluorescence quantum yield in the UV band;

c) high stability to the action of powerful UV radiation.

All these properties are possessed by organic compounds used traditionally to record nuclear radiation and electron streams, namely scintillators. These properties of organic scintillators are in agreement with modern theory of the electronic structure of molecules. The molecules of aromatic and heteroaromatic compounds, such as scintillators, are characterized by the presence of a well conjugated π system. The spectral properties of such molecules (at least up to the vacuum ultraviolet) are determined exclusively by π-π^* transitions, which explains fully the properties listed above. This distinguishes them significantly from molecules of most dyes, in which transitions of other types are possible together with π-π^* transitions (e.g., n-π^*).

3. The first scintillator tested by us for the purpose of obtaining generation was para-terphenyl dissolved in cyclohexane[2,3]. Excitation of the fourth harmonic of a neodymium laser (λ_p = 265 nm) yielded generation at a wavelength λ = 340 nm.

4. By now, generation was obtained with a large number of scintillators. We used for the pumping the fourth harmonic of a neodymium laser[2-4]; the third harmonic of a neodymium laser or the second harmonic of a ruby laser, $\lambda_p \approx 350$ nm[2,3,5-7]; the radiation of an ultraviolet N_2 laser operating both in the single-pulse regime and in a regime with a large pulse repetition frequency[4]; and the radiation from flash lamps[8].

Perhaps the only untested presently-suitable (in principle) scintillator-laser excitation sources were radiation-pumping sources.

5. An important property of lasers using organic compounds in general and scintillators in particular is the possibility of continuously varying the generation frequency in a very wide range. Such a variation was realized in a laser with para-terphenyl[4]. To this end, one of the resonator reflectors was in the form of a diffraction grating with N = 200 lines/mm. Rotation of the grating led to a change of the generation wavelength in the range 330–360 nm, i.e., the range of continuous variation was $\Delta\lambda$ = 300 Å ($\Delta\nu$ = 2500 cm^{-1}) at a generation line width 7 Å. Further narrowing of the generation line is possible, down to hundredths of an Angstrom[9].

6. When account is taken of the possible frequency variation, scintillator lasers realized by now fill entirely the spectral region from 330 to 420 nm. There is no doubt that scintillators can be used to extend the band to 300 nm. It is not presently obvious that still shorter wavelengths can be attained by this method. There is, however, a clear-cut other method for obtaining sufficiently powerful tunable radiation in the region $\lambda < 300$ nm. This is the generation of summary frequencies, by starting with organic-compound lasers and their pumping.

Calculation shows that the standard crystals used in nonlinear optics (KDP, ADP) and the already available organic-compound lasers make it possible to obtain radiation at any wavelength in the range from 215 to 330 nm. Experiments performed in this direction have shown that the conversion efficiency is the same as in harmonic generation, i.e., the radiation of organic-compound lasers has no particular distinguishing features capable of lowering the efficiency of mixing it with the radiation of lasers (or its harmonics) used for pumping.

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A. P. Sukhorukov. Thermal Self-action of Intense Light Waves

The propagation of light waves in absorbing media was investigated until recently within the framework of allowance for the complex character of the dielectric constant. Yet in the case of intense waves it is impossible to disregard the other side of the dissipation processes, namely the heating of the medium. The change in the properties of the medium with increasing temperature, particularly of the refractive index, $n = n_0 + (dn/dT)T$, can greatly influence the conditions for propagation of bounded light beams. Indeed, uneven heating of the medium leads to the formation of thermal lenses that are continuously distributed along the beam.

As shown by recent investigations, thermal effects play a predominant role among other self-action mechanisms, such as the high-frequency Kerr effect,

and electrostriction. Among the distinguishing features of thermal self-actions we can point to the following:

1. Temperature changes of the refractive index are equally effective in all media: liquids, solids, and gases, with $dn/dT = 10^{-4}-10^{-6}$ deg^{-1}.

2. Thermal self-action plays a major role not only in media with large absorption ($\delta \approx 0.1$ cm^{-1}), but also in practically transparent media ($\delta \approx 1$ km^{-1}).

3. The appearance of thermooptical effects can be entirely different, depending on the sign of the derivative dn/dT. In media with $dn/dT < 0$, Gaussian beams become self-defocused, and in media with $dn/dT > 0$ they are self-focused.

4. Thermal lens effects are observed both in fields of continuous radiation with power ~1 W, and in fields of powerful pulses with energy ~1 J. It should be particularly emphasized that thermal self-action put an end to the monopoly of pulsed solid-state lasers in the self-focusing region.

5. It should also be noted that the action of thermal lenses in liquids and gases depends on the motion of the medium due to convection or extraneous sources (wind, currents). This gives rise to a new phenomenon, the bending of the light beam by a lateral wind.

The paper considers a number of problems studied in the Physics Department of the Moscow University[1-4]. It should be stated that our investigations were carried out in parallel with investigations by other Soviet and foreign physicists (J. R. Whinnery, A. G. Litvak, Yu. P. Raĭzer, P. L. Kelley, and others), who made large contributions to the investigated problem.

Let us consider now the main laws governing the course of thermal self-action under different conditions.

1. Thermal self-focusing in solids and $LiNbO_3$ ($dn/dT > 0$). This class of substances includes various types of glasses, the crystal $LiNbO_3$, and others. Some problems in the theory of thermal self-focusing were first considered by Litvak[6].

a) Stationary regime. The distance over which a beam would become focused as a result of only nonlinear refraction can be calculated in simple manner on the basis of the well known formula for inhomogeneous media

$$R_T \approx a\,(n_0/|\Delta n|)^{1/2}, \qquad (1)$$

where $\Delta n = (dn/dT)\Delta T$, ΔT is the temperature difference at the center of the beam and on its periphery, and a is the beam radius. In this case $\Delta T \approx \delta P/\kappa$ and $R_T \approx a[n_0\kappa/(dn/dT)\delta P]^{1/2}$ (κ is the thermalconductivity coefficient and P is the beam power). However, the beam propagation is always influenced by diffraction effects that tend to extend it over lengths on the order of $R_d = ka^2/2$, where $k = 2\pi/\lambda$ is the wave number. For thermal self-focusing of a beam with diffraction divergence it is necessary to have $R_T < R_d$, or the input power of the beam should be larger than the critical value

$$P_{cr} = P_\infty [1-\exp(-\delta R_d)]^{-1}, \quad P_\infty = \lambda\kappa (dn/dT)^{-1}. \qquad (2)$$

In glasses, $P_\infty = 0.01$ W and the necessary laser-beam power does not exceed a fraction of a watt. We recall that in the case of Kerr self-focusing in liquids we have $P_{cr} \approx 100$ W, and in striction self-focusing $P_{cr} \approx 1$ MW.

The field at the focus is limited as a result of attenuation of nonlinear refraction forces relative to the diffraction forces with decreasing beam radius ($R_T/R_d \sim a^{-1}$). Since the nonlinearity of the medium increases with increasing absorption, and the beam power decreases, there is an optimal loss of about 50% of the input power, at which the intensity at the focus is maximal.

In stationary thermal self-focusing, there is no splitting into filaments as in the case of the Kerr nonlinearity. The reason is that the large-scale inhomogeneities of the wave become self-focused more rapidly (increment $\sim(R_T^2 - R_d^2)^{1/2}$); consequently, the beam as a whole collapses before its perturbations have time to develop.

Thermal self-focusing was first observed in 1967 at our laboratory, in the passage of an argon-laser beam with $P < 1$ W through a thin $LiNbO_3$ crystal 4 mm long[1]. In subsequent experiments with long samples of glass, 10–30 cm long, conditions of internal self-focusing were realized (first in the USA[8,9] and somewhat later by our group[3]).

b) Nonstationary regime. The temperature gradient is established in the beam after the start of the laser pulse, within a time

$$\tau_T \approx \rho c_p a^2/\varkappa \qquad (3)$$

(at a = 1 mm in glasses, $\tau_T \approx 1$ sec). Obviously, for pulses of duration $\tau_p \ll \tau_T$ the thermal conductivity becomes negligible and $\Delta T = (\delta/\tau_T)\int_{-\infty}^{t} P dt$. In this case the focal distance $R_T(t)$ decreases monotonically during the time of the pulse, and the minimal self-focusing length depends on the total pulse energy. For this reason, the condition for the nonstationary self-focusing contains the energy, which is connected with the critical power by the relation

$$W_{cr} = P_{cr}\tau_T. \qquad (4)$$

Usually it is necessary to have initial energies ~0.01 J. In the focal region, where the beam radius decreases strongly, the time of the nonstationary regime becomes quite small and the mechanism of thermal conductivity begins to play an important role, limiting the field at the focus ($a_f \sim a(\tau_p/\tau_T)^{1/2}$).

The foregoing features of thermal self-focusing of the pulses are important, in particular in the study of the picture of crystal breakdown[10].

2. Liquids. In liquid media, as a rule, $dn/dT < 0$, which leads to defocusing of the continuous radiation. The critical power, just as in the case of solids, amounts to a fraction of a watt.

Liquids have been the subject of the largest number of both experimental and theoretical studies. Studies of thermal self-focusing date back to 1965[5]. By now there has been developed a detailed theory of most observed phenomena. An analysis has been made of spherical aberrations of thermal lenses, of the dependence of the beam divergence on its power, absorption, and length of the medium.

The last of these effects is the basis of a procedure for measuring extremely small absorptions by pure liquids, $\delta \approx 10^{-4}$ cm^{-1}, by investigating the far field of a beam passing through a cell with the liquid.

The defocusing picture becomes strongly distorted when convective streams are produced, especially if the beam propagates horizontally.

The theory of nonstationary defocusing of pulses was first developed by Raĭzer[7]. He analyzed the competition between thermal defocusing and the Kerr effect, as well as other features of these phenomena.

3. Gases. Temperature variations of the refractive of gases, for example air, are also quite large: $dn/dT \approx 10^{-6}$ deg^{-1}. However, the absorption of pure dry air in the transparency windows is exceedingly small: $\delta \approx 0.1$ km^{-1}. For a narrow beam with $a \approx 1$ mm and $\lambda \approx 1\ \mu$ we have $\delta R_d \approx 10^{-4}$, i.e., only 10^{-4} of the input power is absorbed in the Fresnel zone of the beam. Therefore, although $P_\infty = 0.01$ W as before, the critical powers increase strongly, to 100 W. Thus, under laboratory conditions, thermal effects in air become manifest at the level of the continuous-radiation power, ~1 kW. In the nonstationary case ($\tau_p < \tau_d$) we have $W_\infty = 10^{-4}$ J and $W_{cr} \approx 1$ J.

Under natural conditions, the situation changes significantly, owing to the constant presence of winds with velocity $v \approx 1$ m/sec. The incoming wind stream becomes heated in the region of the beam within a time $\tau_w \approx a/v$, and then leaves this region, carrying away the thermal lenses. On the windward side, the medium is colder, and the refractive index is larger than at the center of the beam. As a result, the light beam becomes deflected in a direction opposite to the motion of the absorbing medium (in a medium with $dn/dT > 0$ the beam would be deflected in the wind direction). This effect was observed experimentally in liquid streams[3].

The critical wind velocity (from the condition $\tau_w = \tau_T$) is inversely proportional to the beam radius (in air $v(m/sec) \approx 1/10a$ (mm)). We see that natural wind will practically always influence the thermal self-action of continuous radiation. When wind is taken into account, the critical power of thermal effects increases strongly, by one or two orders of magnitude: $P_{cr,w} = P_{cr}\tau_T/\tau_w$.

In the case of propagation of a short pulse ($\tau_p \ll \tau_w$), the influence of the wind is negligible, and the increase of the pulse energy over the critical value (4) is important.

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