Erbium glass lasers and their applications

V.P. GAPONTSEV, S.M. MATITSIN, A.A. ISINEEV, V.B. KRAVCHENKO

In this paper results of experimental investigations into erbium glass lasers and their likely applications are discussed. Regularities of the inversion energy accumulation, also as channels of energy losses, are covered in detail. Different erbium lasers, both flashtube and neodymium laser-pumped, are compared. Parameters of some erbium laser glasses are presented, including the new LGS-E7, which requires a smaller pumping energy density (less than 100-200 J cm^{-2}). Test data from experimental models are summarized.

KEYWORDS: lasers, erbium glass, neodymium

Introduction

Erbium glass lasers (EL) have been known since 1965, when Snitzer and Woodcock first obtained laser action of Er^{3+} ions in silicate glass[1]. Immediately specialists turned their attention towards achieving a suitable spectral range (λ_{em} = 1540 nm) which was safe for eyes and could be easily detected[2-10]. However, the development of effective ELs was found to be a much more difficult problem than compared with neodymium lasers (NL). Interest of most designers was short-lived, and for a long time investigations were continued by only a narrow circle of scientists[11-17], which was insufficient to achieve fast progress in this field. Only recently has a high level of understanding of the physical processes within the erbium active medium been achieved. Also, high-quality erbium glasses (EG) have now been fabricated to allow different modes of operation and the introduction of some effective laser systems[17-23].

This paper reviews new results achieved in the field of EL. It is based mainly on data from our Institute.

Parameters of erbium glasses and regularities of the inversion energy accumulation

Figure 1 shows a simplified representation of energy states and transitions, which illustrates the processes taking place in the erbium active medium at high excitation. This is much more complicated than the four-level one for NL. The laser action of Er^{3+} is produced by the resonant transition $^4I_{13/2}-{}^4I_{15/2}$. The fluorescence of higher states is practically fully quenched by the process of non-radiative multiphonon relaxation, which has a rate[18] of more than 10^5-10^7 s^{-1}. So, in contrast to crystals[24], there is only one transition, suitable for laser action for Er^{3+} in glasses*

Some data on the fluorescence characteristics of this transition are listed in Table 1. As one can see, the maximum available values of erbium quantum efficiency are not far from unity in all glasses except borate ones. Fluorescence lifetimes for $^4I_{13/2}$ are 10^{-2} s, about 20 times greater than lifetimes of NG. The concentration quenching in erbium luminescence is not present in EC of high purity. Moreover, the effective value of τ_{Er} may even be higher than the tabulated values because of the effect of reabsorption[25]. The most serious quenchers are admixed OH-groups, whose concentration must not be more than 3-5 x 10^{18} cm^{-3} [25,26]. This makes the technology of EG manufacturing more demanding. The mechanism of quenching by OH-groups, is defined in Ref. 27. Fig. 2 shows the dependence of τ_{Er} on the concentration of OH-groups in phosphate EG with different concentrations of Er^{3+} (N_{Er}). The increase in quenching with increasing N_{Er} can be explained by the energy migration.

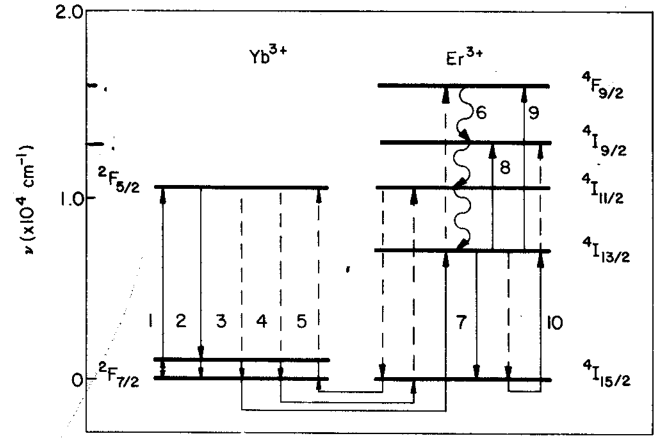

Fig. 1 Schematic representation of the erbium active medium. Solid arrows correspond to induced (1, 8, 9) or spontaneous (2, 7) transitions, wavy lines to non-radiative transitions (6), and dashed lines to energy transfer processes: cumulative (3), sensitization (4), back transfer (5), and non-linear quenching (10)

Table 1 also lists the highest values for induced emission cross-section σ_{em}. The dependence of σ_{em} on the glass composition is very small: the highest σ_{em} values correspond to transition on the lowest component of the multiplet $^4I_{15/2}$.

So, the operational scheme of EL is clearly three-level (λ_{em} = 1536 nm). The presence of the 1543 nm line in the emission spectrum does not change the situation because it is connected with the second stark component lying higher on 25-30 cm^{-1} only. It is therefore necessary to

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* It is also possible to obtain lasing on the transition $^4I_{11/2}-{}^4I_{13/2}$, λ_{em} = 2700 nm, in tellurite glasses.

The authors are at the Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR, Moscow, GSP-3, 103907, USSR. Received 2 February 1982.

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Table 1. Some parameters of erbium laser glasses

Glass	τ_{Er} $(10^{-3}s)$	η_{Er}	σ_{em} $(10^{-20}cm^2)$	C_q $(10^3 nm^6 s^{-1})$	W_{MR} $(10^5 s^{-1})$	W_B/W_{MR}	$\bar{W}_s$ $(10^3 s^{-1})$	$(N_{Er})_{min}$, $(10^{19} cm^{-3})$
Na-K-Ba-silicate	14	1	0.56	1	1	2	2.0	7
ED-2 (silicate)	12	1	0.65	1.6	0.9	2.2	3.0	5
Na-Mg-phosphate	8.2	0.83	0.65	1.9	8	0.25	10.5	2.7
LGS-E (phosphate)	7.7	0.88	0.70	2.1	10	0.2	10.9	2.5
LGS-E7 (phosphate)	7.9	0.86	0.75	2.0	10	0.2	10.8	2.5
Fluorosphosphate	8.0	1	0.67	2.0	–	–	1.9	7
Ba-La-borate	0.59	0.07	0.50	2.2	100	0.02	18	1.9
Na-K-Ba-Al-germanate	6.5	1	–	1.8	0.2	10	2.9	6

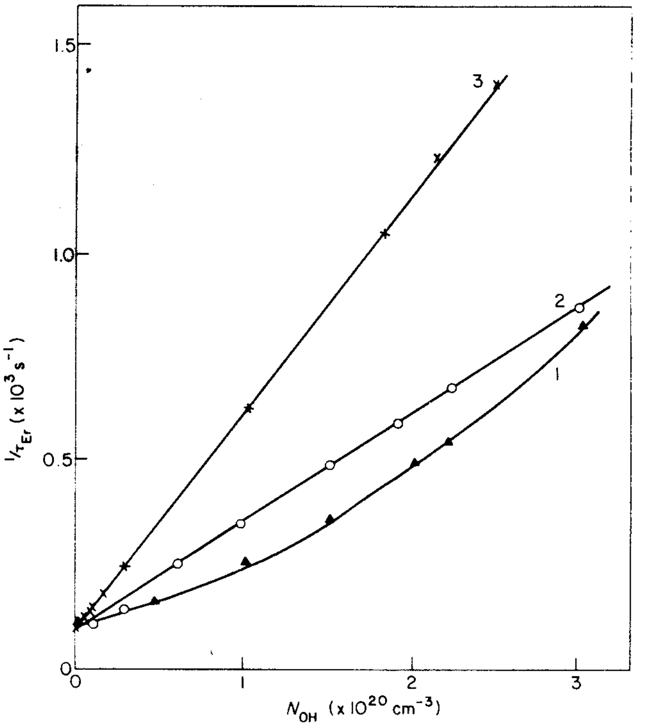

Fig. 2 Dependence of fluorescence lifetime τ_{Er} on concentrations N_{OH} of OH-groups in phosphate glass with $N_{Er} = 0.12(1), 1.2(2), 2.9 \times 10^{20} cm^{-3}(3)$

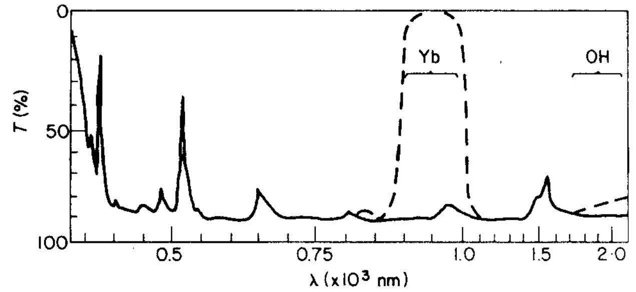

Fig. 3 Absorption spectrum of phosphate erbium glass LGS-E1 with $N_{Er} = 3 \times 10^{19} cm^{-3}$ and $N_{Yb} = 1.3 \times 10^{21} cm^{-3}$. Length of sample is 10 mm

excite more than half the Er^{3+} ions to achieve inversion. Meanwhile, the efficiency of the direct pumping of Er^{3+} is quite low because of its weak and rare absorption bands (Fig. 3). For this reason the excitation of EG is mainly or wholly carried out through the sensitizer ions of Yb^{3+} which have one intense absorption band in the spectral range 900-1030 nm with an effective width of about 1200 cm^{-1}.

The concentration of Yb^{3+} ions (N_{Yb}) usually exceeds 1-1.5 × 10^{21} cm^{-3}, which leads not only to a high level of absorption in the pumping band, but also to fast non-radiative energy transfer in the system of Yb^{3+} and Er^{3+} ions due to energy migration through the donor sub-system. The rate $\bar{W}_s$ of such a sensitization process exerts a decisive influence on the power characteristics of EL. Regularities of the system at a low level of pumping, have been studied in detail[18,28]. It has been shown that because of dependence on N_{Yb} and glass composition, the transfer process has a jumped migration-controlled or supermigrational character. One can observe the transition between two modes, with N_{Yb} between 1.2-1.4 × 10^{21} cm^{-3}, in phosphate glasses (Fig. 4). It has also been shown that the value of $\bar{W}_s$ depends strongly on the glass composition,

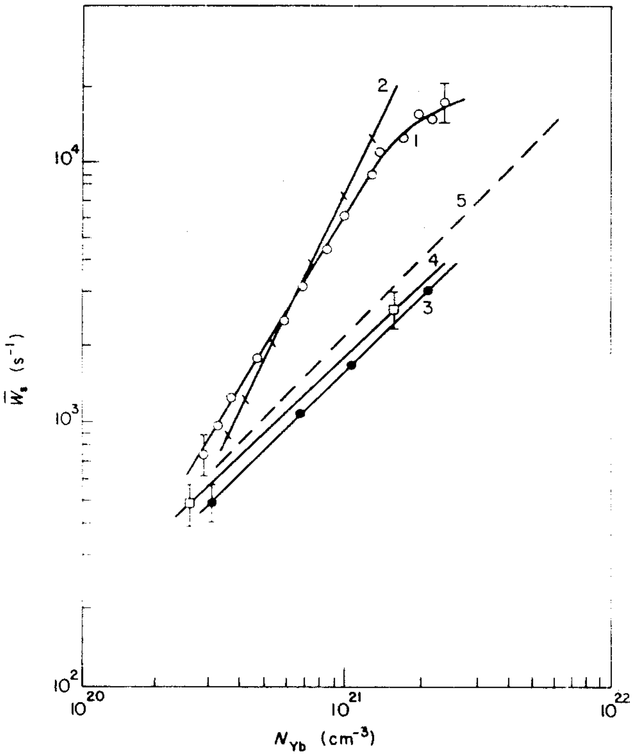

Fig. 4 Experimental dependence of quenching rate $\bar{W}_s$ on concentration of Yb ions in phosphate (1), borate (2), fluorophosphate (3), and silicate (4) erbium glasses. Line (5) corresponds to linear dependence. $N_{Er} = 3.5 \times 10^{19} cm^{-3}$

increasing by a factor of ~ 10 in the set of germanate-silicate-fluorophosphate-phosphate-borate glasses (see Table 1). Moreover, for this set the function $\bar{W}_s = f(N_{Yb})$ changes from linear dependence to a quadratic one. In contrast, the function $\bar{W}_s = f(N_{Er})$ proves to be linear in all glasses.

There was no explanation of this result for a long time, especially as our investigations into the elementary transfer of the Yb^{3+} and Er^{3+} couple had shown very small dependence of its rate C_q on the unit distance from the glass composition (Table 1). Only recently have we determined that $\bar{W}_s$ is mainly dependent on the ratio W_{BT}/W_{MR}, where W_{BT} is the rate of back transfer $[Er(^4I_{11/2}-^4I_{15/2}) \rightarrow Yb(^2F_{7/2}-^2F_{5/2})]$, and W_{MR} is the rate of the multiphonon relaxation between states $^4I_{11/2}$ and $^4I_{13/2}$. It should be noted that within the typical values of N_{Er}, 2-10 x 10^{19} cm^{-3}, the back transfer process has a static character and its rate is limited by the minimum possible distance R_{min} between rare-earth ions in the host material[18]:

$$W_{BT} = 8.5\, C_q N_{Yb} R_{min}^{-3} \qquad (1)$$

Values of W_{MR} and W_{BT}/W_{MR} for $N_{Yb} = 1.5 \times 10^{21}$ cm^{-3} are presented in Table 1. It can be seen that $W_{BT}/W_{MR} > 1$ for silicate and germanate glasses. This reduces the effective value of $\bar{W}_s$ to the magnitude of $W_s W_{MR}/W_{MR} + W_{BT}$ because of the known effect of excitation capture [29]. It is evident that the relative influence of this factor rises with increasing N_{Yb}.

The strong dependence of $\bar{W}_s$ on glass composition leads to differences in the minimum values of N_{Er} which correspond to quantum efficiency of sensitization close to unity ($\eta_s \geqslant 0.9$). As one can see from Table 1, phosphate EG have a considerable advantage in this respect. These glasses also have a higher value of σ_{em}.

Results of investigations into inverse energy storage regularities (Fig. 5) show other more important advantages of phosphate glasses. It has been shown that the experimental dependence $n^*/N_{Er} = f(E_a/V)$ differs sharply from that calculated (curve 6), obtained by taking into account the depletion of the erbium terminal state only. It is also strongly dependent on glass composition. If in known phosphate glass LGS-E1, with $N_{Er} = 6.6 \times 10^{19}$ cm^{-3}, a value of $n^*/N_{Er} = 0.7$ is achieved with an absorbed energy about 1.5 times higher than that calculated, then in silicate glass this energy will exceed the calculated value by about 4 times, and it is not possible to obtain even an inversion in germanate glasses.

The reasons for such great dispersion in the regularities of energy accumulation were discovered by us during investigations of the Yb^{3+} fluorescence decay dependence on n^*/N_{Er} (Fig. 6). At high n^* there appeared to be a new source of quenching, namely, cumulative transfer through the process (Fig. 1) $Yb(^2F_{5/2}-^2F_{7/2}) \rightarrow Er(^4I_{13/2}-^4F_{9/2})$. Moreover, the value of $\bar{W}_s$ decreases very quickly, because the relationship $\bar{W}_s = f(n^*/N_{Er})$ (curve 4) is not linear. Its deviation from a straight line (curve 3), which was based on the linear law $\bar{W}_s = f(N_{Er})$, is caused by the wide dispersion of energy collection rates by Er^{3+} sites from donor surroundings. As a result, the Er^{3+} ions with higher rates are excited initially, and then do not participate in the transfer process due to lack of energy migration in the erbium sub-system. This factor leads to the fast decrease in $\bar{W}_s$.

These effects are sufficient to explain the accumulation dependences in phosphate glasses. Fig. 5 shows the calcula-

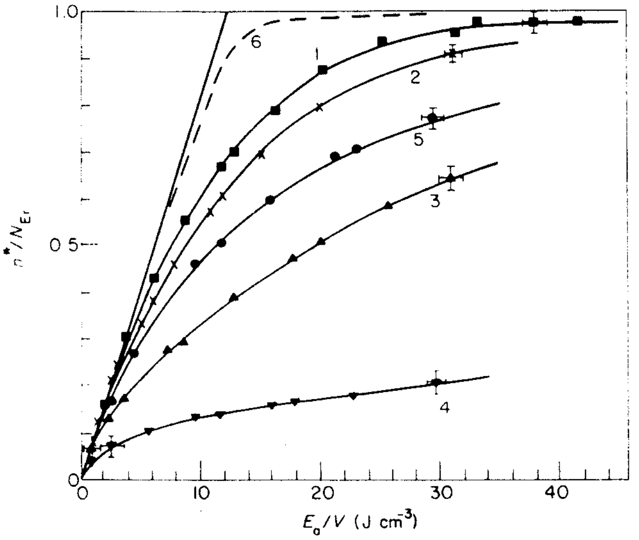

Fig. 5 Experimental (points) and calculated (lines) curves of top population of excited state $^4I_{13/2}$ versus specific absorbed energy E_a/V for glasses: LGS-E7 (1), LGS-E1 (2), silicate (3), germanate (4) and fluorophosphate (5), (6) is the calculated curve for phosphate glass only taking into account the effect of terminal state depletion. $N_{Er} = 6.6 \times 10^{19} cm^{-3}$

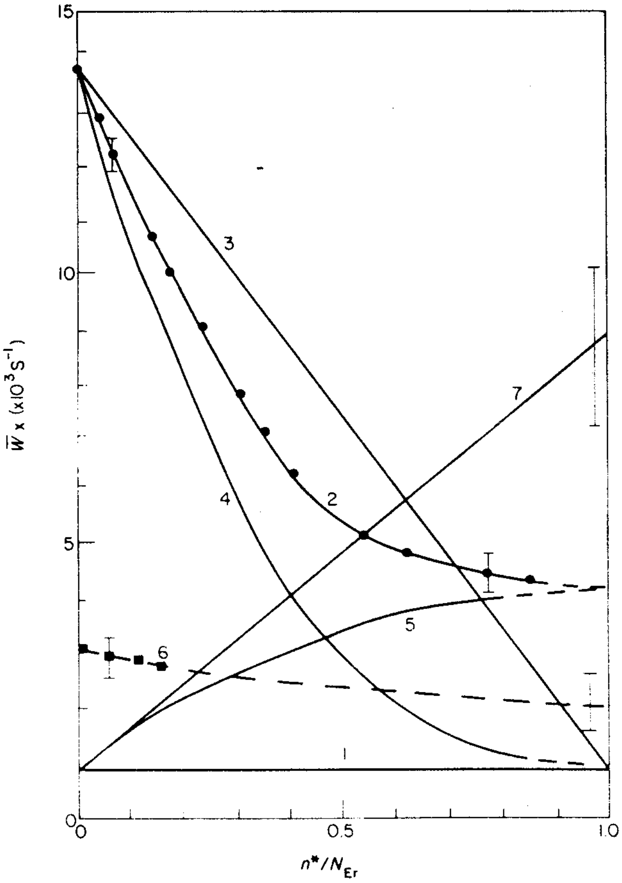

Fig. 6 Dependence of various rates of Yb^{3+} quenching ($\bar{W}$) on the relative level of excitation for phosphate (1-5) and germanate (1, 6, 7) glasses. 1 – radiative decay, 2, 6 – experimental data for $\bar{W}$, 3 – calculated curve only taking into account depletion of the terminal state, 4 – calculated curve for $\bar{W}_s$, 5, 7 – calculated curve for cumulative process. $N_{Er} = 3.8 \times 10^{19} cm^{-3}$ (phosphate glass), $3.4 \times 10^{19} cm^{-3}$ (germanate glass)

ted curve (curve 2), for the glass LGS-E1, which was made by using the relationship $\eta_s = W_s/W_s + W_c + W_1$, where W_c is the transfer rate in the cumulative process, and W_1 is the radiative rate of Yb^{3+} in glasses without quenchers. This curve coincides closely with measured points. The more difficult situation is in the case of germanate and silicate glasses. One has to take into account here the contribution of the back transfer process. When $W_{BT}/W_{MR} > 1$ a large proportion of Er^{3+} ions, excited to the state $^4F_{9/2}$ as a result of the cumulative process, relax to the ground state by-passing the metastable state. So, cumulative interactions not only considerably reduce the number of excited Yb^{3+} sites, but also Er^{3+} ones. This new form of quenching additionally reduces the accumulation efficiency (silicate glasses), and when $W_{BT}/W_{MR} \gg 1$ can lead to saturation even at the level of 0.2-0.3 N_{Er} (germanate glasses). The validity of such a model is confirmed by the correlation between measured points for germanate glass and the calculated curve (Fig. 6, curve 4), obtained by using $W_c = f(n^*/N_{Er})$ and $\overline{W} = f(n^*/N_{Er})$.

Thus, our investigations into energy transfer and accumulation regularities in different EG have shown that accumulation efficiency, and hence power characteristics, of EL depends much more on the choice of the composition of the glass than is the case with NL. Phosphate glasses thus have decisive advantages in comparison with other systems.

Although there proved to be some small differences in the accumulation efficiency in the set of phosphate glasses, optimization of glass composition allows us to improve slightly the accumulation conditions. This can be seen in the example of our new phosphate glass LGS-E7, made recently (Fig. 5, curve 1). In this case the relative rate of the cumulative process is about 2.5 times lower than for LGS-E1 glass.

It should also be noted that phosphate EG allow us to attain what appears to be the optimum requirement for the inversion energy accumulation

$$\overline{W}_s^{-1} \ll \tau_p = (1\text{-}1.5)\,\mathrm{ms} \ll \tau_{Er} \tag{2}$$

where τ_p is the pumping pulse duration. This requirement allows us to neglect the influence of non-linear erbium quenching $[Er(^4I_{13/2}) + Er(^4I_{13/2}) = Er(^4I_{9/2}) + Er(^4I_{15/2})]$ on the accumulation process[30] because under such conditions this quenching is important only when N_{Er} is above 6-8 x 10^{19} cm^{-3}. One may also neglect, within limits of course, losses by amplified spontaneous emission[21]. Finally, Fig. 7 shows the calculated relationship between N_{Er} and the specific absorbed energy E_a that is necessary to achieve the inversion level. These relations seem to be useful for the optimization of EL.

Erbium lasers with lamp pumping (ELL)

It can be seen from Fig. 7, that even for the best EG the minimum value of N_{Er} is about 2.5-4 x 10^{19} cm^{-3}. So, taking into account cavity losses, one must excite more than 1.5-2 x 10^{19} cm^{-3} of Er^{3+} ions to reach the emission threshold. This concentration exceeds that usual for NL by more than an order of magnitude. If we take into account the low coefficient of pumping utilization, then even in the presence of sensitizer ions (Yb^{3+}) the laser-action threshold of ELL proves to be very high. Within the limited durability of xenon flashtubes, it is really only reached with laser rods of small diameter ($d \leqslant 10$ mm).

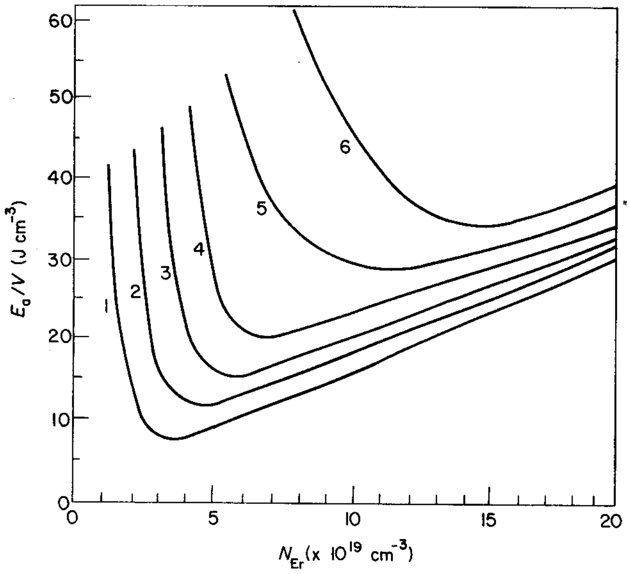

Fig. 7 Calculated relations between N_{Er} and specific absorbed energy E_a/V for phosphate glass at different inversion levels

High values of N_{Yb} also restrict d because rods with $d \geqslant 7$-8 mm are excited uniformly already.

Thus, possibilities of ELL are limited and efficiency is lower than with NL. As an example, we can give the data for ELL with a 6.5 x 80 mm laser rod of LGS-E1 glass ($N_{Yb} = 1.5 \times 10^{21}$ cm^{-3}, $N_{Er} = 3 \times 10^{19}$ cm^{-3}) which was enclosed in a cylindrical quartz reflector, coated with Ag and cooled by running D_2O. The base of the cavity was about 300 mm, and reflection from the output plane mirror was 70%. In such an ELL system, with $\tau_p = 4$ ms, the threshold was achieved at an electric pump energy E_p of about 350 J, and an output of 1.8 J was obtained in 3.1 ms with 1200 J pumping. In a Q-switching operation using a revolving quartz prism, an output of 0.8 J with $\tau_{em} = 30$ ns and $E_p = 800$ J was obtained.

Methods to increase flash-pumping efficiency have been considered. One of these involves using a second sensitizer – Nd^{3+} ions[7]. Unfortunately, erbium fluorescence quenching through the channel $Er(^4I_{13/2}\text{-}^4I_{15/2}) \rightarrow Nd(^4I_{9/2}\text{-}^4I_{15/2})$ occurs, which is undesirable for Q-switched operation. As regards the free-operation of ELL, its influence could be compensated for with $N_{Nd} \leqslant 4 \times 10^{20}$ cm^{-3} by means of a decrease in τ_p.[12] However, the introduction of Nd^{3+} causes additional cavity losses at 1540 nm of about 1.5-2 x 10^{-3} cm^{-1} with $N_{Nd} = 1 \times 10^{20}$ cm^{-3}. Due to the small values of σ_{em} (see Table 1) these losses considerably influence ELL efficiency, so it is undesirable to use $N_{Nd} > 5 \times 10^{19}$ cm^{-3}. Snitzer et al[4] considered the optimum value of Nd^{3+} to be about 2 x 10^{19} cm^{-3}, and this improved performance by up to 3 times. That study of ELL used a 4 x 76 mm rod of Zn-Al-phosphate glass (15% wt Yb_2O_3, 0.5 % wt Er_2O_3, 0.2 % wt Nd_2O_3). With $\tau_p = 6$ ms, the threshold was reached at 95 J, and at 350 J a free-operation output of 0.8 J was obtained. In Q-switched applications, ELL emitted about 0.2 J in 25 ns when pumped by 150 J. Similar data can be found elsewhere[5-10].

Another method to increase ELL efficiency is the use of radiatively transferring claddings, made from glasses, activated by Nd^{3+} and Yb^{3+} [7], or Mo^{2+} [31], for example. An improvement of up to two times was obtained by using Nd-Yb-cladding[7]. This could obviously be greater if one were to use high-activated glass for cladding with a lowered concentration quenching of Nd^{3+}.

An attractive way of increasing ELL output is to use tubular rods, for example, with emitting cores. It allows the use of flashtubes of large diameter which permits greater pump energy. In this way we have achieved output of 4 J in 3.5 ms from a 12 cm long rod with external diameter of 14 mm and internal diameter of 8 mm.

Finally, it must be noted that power properties of ELL have been insufficiently studied at the present time. Possibilities for improvement are connected with the development of (i) improved reflectors; (ii) interference coatings of tubes, or rods, which could stimulate the transformation of unused pump radiation to the absorption band of Yb^{3+} ions; (iii) inside-hollow flashlamps, which have emissions corresponding closely to the spectral range of EG pumping[18]; (iv) glasses with additional sensitizers, for example Cr^{3+}.

Erbium laser converter (ELC)

The decisive improvement in EL energy parameters was achieved through excitation by NL free-operation emission[11]. In this case the pumping emission is absorbed by Yb^{3+} ions at the transition $^2F_{7/2}/4/ \rightarrow {}^2F_{5/2}/1/$ (Fig. 1). In spite of the low thermal population of the fourth stark component of $^4F_{7/2}$ at 300 K ($\approx 0.015\text{-}0.020\, N_{Yb}$), in some EG the specific absorption coefficient at $\lambda = 1054\text{-}1060$ nm may be made large enough ($k_p \approx 5 \times 10^{-2}$ cm^{-1}) by introducing high values of N_{Yb}. Theoretically the coefficient of energy conversion is defined by the ratio $\eta = \lambda_p/\lambda_{em} = 0.69$. Although such a value, under real conditions, is unlikely, the use of laser pumping allows us to make an ELC with good energy parameters thanks to high NL efficiency in the free-operation mode (up to 5%), and also to remove the limitation on the dimensions of the erbium active element (AE).

Another advantage of laser pumping is the low specific thermo-emission in the AE, and hence its small thermal distortion. This allows a decrease in beamwidth and a rise in the pulse repetition rate.

The advantages of ELC are particularly evident for large-power amplifiers of short and ultra-short pulses ($10^{-8}\text{-}10^{-12}$ s). Large values of τ_{Er} and η_{Er} at moderate σ_{em} make EG close to the ideal medium for this mode of operation, which in combination with laser pumping makes it possible to store more than 10 J cm^{-3} in the $^4I_{13/2}$ state with a specific gain coefficient of up to 0.5-0.6 cm^{-1} (see Fig. 5). These values greatly exceed those for neodymium glass amplifiers, which, as is known, do not truly satisfy the requirement for an amplifying medium[32].

However, the development of effective ELC is dependent on the difficult task of forming an optical conjunction of NL and EL cavities. It is first necessary to arrange complete and uniform absorption of the pump emission into the erbium AE. The best method of achieving this is to put the latter inside the NL cavity. The maximum efficiency condition of NL, operating with such loading, is

$$k'_p = k_p l_p / L \gg \beta_1 + \beta_2 l_p / L \qquad (3)$$

where β_1 and β_2 are loss coefficients at λ_p accordingly for neodymium and erbium AE, L and l_p are the lengths of these AE in the direction of pumping, and k'_p is the coefficient of useful losses, carried by erbium AE in the neodymium laser cavity. With typical values of $\beta_1, \beta_2 \cong 10^{-3}$ cm^{-1}, $L = 260$ mm (LGS-E1 glass), $k'_p \geqslant 10^{-2}$ cm^{-1} can be achieved with $l_p > 45$ mm. For one pass in erbium AE about 45% of the pumping energy is absorbed and its density at input and output differs by less than 20%. There is a possibility of reaching a more uniform excitation ($\leqslant 5\%$) if a symmetric disposition of two neodymium AE's about the erbium AE is used (Fig. 8). Thus, the above-mentioned value of k_p enables uniform pumping of large volumes of EG, making easier the task of constructing an ELC with high emitted energy ($E_{em} \geqslant 20\text{-}30$ J).

However, more moderate values of E_{em} and AE lengths are required for many applications. In these cases it is desirable to have EG with greater k_p. It has been shown[20] that in a set of phosphate glasses the absorption cross-section σ_p at λ_p is not changed significantly, and the only way of increasing k_p is to increase N_{Yb}. However, in most of the compositions it is not possible to introduce more than 2×10^{21} ions cm^{-3} of Yb^{3+} without reducing their technological properties, and their readiness to crystallize. Only recently has phosphate EG(LGS-E7) been found in which N_{Yb} can reach a value of 4.3×10^{21} cm^{-3}, and k_p a value of 0.17 cm^{-1},[20]. Erbium elements prepared from this EG combine well with NL even at $l = 1.0\text{-}1.5$ cm, because the required pump energy for $L = 12\text{-}15$ cm can be provided in this case.

A further increase in k_p is possible by the use neodymium glasses in NL with their fluorescence maximum λ_{max} displaced to the short-wave region, or by using AE heating[18]. So, in the LGS-E7 glass at $T = 80°$C, $k_p = 0.28$ cm^{-1} with $\lambda_p = 1055$ nm.

It was assumed above that NL emission is concentrated around λ_{max}. However, the selective character of active losses, induced by the erbium AE, which intensify according to the usual relationship $dk'_p(\lambda)/d\lambda > d\alpha'(\lambda)/d\lambda$, where $\alpha'(\lambda)$ is the specific gain coefficient of the neodymium AE at λ, leads to a situation such that the threshold condition for NL, $\alpha'(\lambda) \geqslant k'_p(\lambda)$ is first fulfilled in the long-wave region of the gain line ($\lambda = 1070\text{-}1080$ nm) (Fig. 9). As a result, the NL emission spectrum is widened to 15-20 nm, and its central λ_p value is moved to 1062-1065 nm[14,18]. For the stabilization of λ_p at λ_{max} it is necessary to put elements with back dispersion $k''_p(\lambda)$ in the NL cavity. In this case

$$\frac{d(k'_p(\lambda) + k''(\lambda))}{d\lambda} < \frac{d\,\alpha'(\lambda)}{d\lambda} \qquad (4)$$

Elements that have been used are: specially prepared mirrors for the NL resonator with $R_{1054nm} \geqslant 0.98$ and $R_{1070nm} \leqslant 0.4$; glass plates, activated by Sm_2O_3[18]; the Fabry-Perot etalon[21].

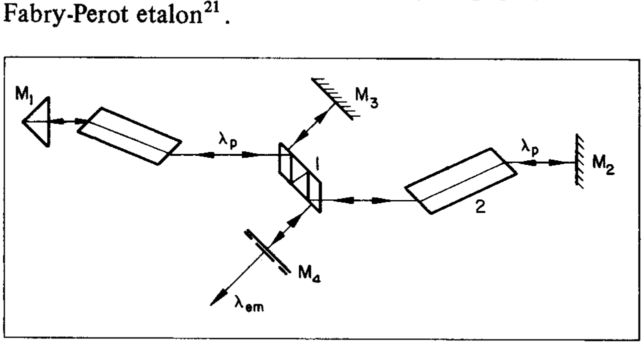

Fig. 8 Scheme of erbium laser with symmetric inside-resonator pumping of active element. 1 — erbium element, 2 — neodymium elements, M_1 — 90° prism, M_2 to M_4 — plane mirrors

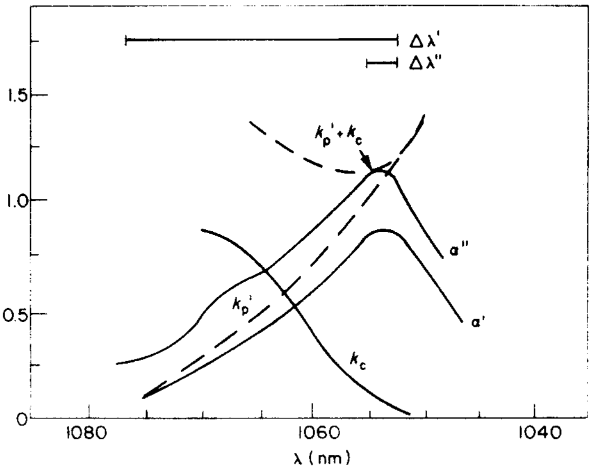

Fig. 9 Spectral dependences of gain (α', α'') and ytterbium-induced absorption (k'_p) coefficients for ELC with inside-resonator pumping. k'_c is reflection loss introduced into the resonator by the compensating element (mirror). $\Delta\lambda'$ and $\Delta\lambda''$ are spectral widths of emission of NL respectively without and with compensating element

Among other factors that can influence the effective value of k_p for laser pumping, is the absorption of pumping emission by Er^{3+} ions from the state $^4I_{13/2}$ to $^4F_{9/2}$. Its maximum is in the range 1130-1140 nm, but the shortwave region stretches up to 1040 nm. Measurements have shown that in phosphate glasses at λ_p this absorption does not exceed 10^{-2} cm^{-1} when $n^* = 3 \times 10^{19}$ cm^{-3}. The back influence, or the reduction of k_p, is caused by the effect of the stark population balancing ($^2F_{7/2}/4/$ and $^2F_{5/2}/1/$), which is important when the pumping rate $W_p = \sigma_p E_s/\tau_p h\nu_p \geqslant (0.2\text{-}0.3)\,\bar{W}$, where $\sigma_p = k_p/N_{Yb}\exp(-\Delta E_{41}/kT)$ and E_s is the density of pump emission, in J cm^{-2}.

The danger of this happening may be estimated with an example of LGS-E1 glass where $N_{Er} = 3.6 \times 10^{19}$ cm^{-3} and $k_p = 0.06$ cm^{-1}. Using the data from Fig. 5, the inequality $W_p \geqslant 0.2\,\bar{W}$ with $\tau_p = 10^{-3}$ s is fulfilled when $E_s = (130\text{-}150)$ J cm^{-2}. Comparison of this estimate with values of $E'_s = 80$ J cm^{-2} for the inversion threshold and $E''_s = 180$ J cm^{-2} for $n^*/N_{Er} = 0.8$ shows that the requirement $W_p < 0.2\,\bar{W}$ is critical. One method of achieving this is to increase τ_p. In the free-operation mode this is quite allowable (optimum values of τ_p are here about 4-6 ms), but in the short-pulse amplification mode it is extremely undesirable because it breaks another condition of effective energy accumulation, $\tau_p \ll \tau_{Er}$. A compromise in this case is $\tau_p = (1.5\text{-}1.7)$ ms.

A more radical way is to increase k_p thereby reducing the required value of E_s. Note that very high E_s values are a serious problem, hindering the creation of an effective ELC due to a number of reasons, one of which is the proximity of E_s to the threshold of EG destruction caused by platinum particles (about 500-700 J cm^{-2}). On the other hand, required values of E_s mainly in the free-operation mode (up to 800-900 J cm^{-2} for LGS-E1 glass) are usually attained with difficulty. This factor compels us to consider the possibility of pump-beam compression into the erbium AE, and what is more, without the introduction of additional losses into the NL cavity.

Figure 8 illustrates one of the possible arrangements. The erbium AE is prepared as a special prism, and inside this the E_s value exceeds the input value of E_s by about 2 times because of full inner reflections of the pumping beam from side facets, on which the last one falls at 45°. This simultaneously provides a raised pump uniformity, and solves the problems of dividing the pumping and emission beams. The disadvantage of such an arrangement is the complexity of manufacturing a number of working facets, and the need to use a neodymium AE of rectangular section.

As an example, we show the results of tests on one ELC model using such a scheme. The erbium AE was made from LGS-E1 glass with $N_{Er} = 2.5 \times 10^{19}$ cm^{-3} and $\beta_1 \leqslant 2 \times 10^{-3}$ cm^{-1}. The pumped volume was 8.2 cm^3, and l_p was 12.8 cm. Neodymium elements of LGS-E1 glass had a rectangular form with dimensions 10 x 32 x 280 mm. Their faces were set at the Brewster angle. The NL resonator base was 150 cm, and the ELC resonator base 20 cm. The latter was formed by plane dielectric mirrors M_3($R = 1$) and M_4 ($R = 0.6$). The mirror M_2 had $R_{1054nm} = 0.95$ and $R_{1070nm} = 0.4$. At $\lambda_p = 3.5$ ms and $E_s = 600$ J cm^{-2} an output of about 80 J, with a slope efficiency of ~39% and beam divergence of less than 3×10^{-4} rad was achieved[17]. There were three lines, 1536 ± 0.8 nm, 1543 ± 0.9 nm, and 1538 ± 0.7 nm, in the emission spectrum.

Erbium glasses with higher values of k_p allow the use of simpler pumping schemes, particularly that of Fig. 10. Here, additional mirrors M_3 and M_4, with $R_{1055nm} = 0.99$ and $R_{1540nm} = 0.15$, remove pump losses due to reflections from the faces of the erbium AE, placed at an angle of 8° to the optical axis of the NL resonator. Results of comparative tests of LGS-E1 and LGS-E7 glasses ($N_{Er} = 3.3 \times 10^{19}$ cm^{-3}) in free operation are presented in Fig. 11. The erbium AE

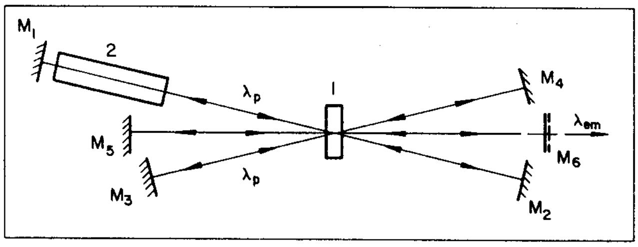

Fig. 10 Pump scheme for ELC with the high-absorbing erbium glass. 1 – erbium element, 2 – neodymium laser, M_1 to M_6 – selective mirrors

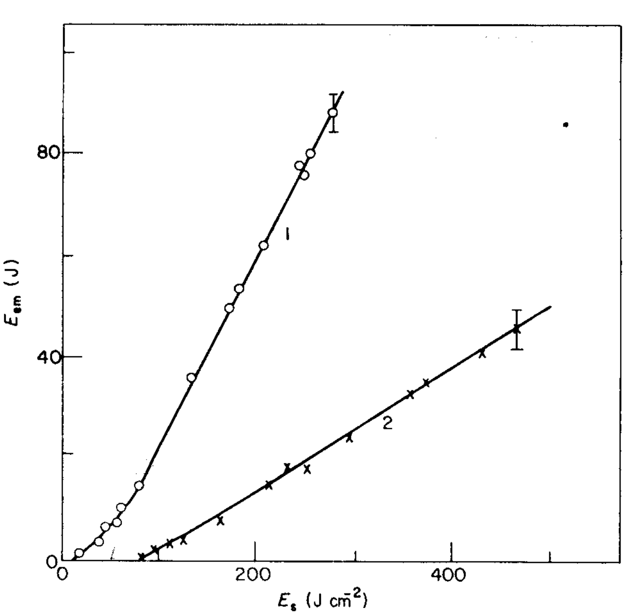

Fig. 11 Experimental dependence of output-emitted energy of erbium long-pulse laser converter versus E_s value for LGS-E7 (1) and LGS-E1 (2) glasses

was prepared as discs with diameter of 10 cm and l_p = 3.1 cm. NL provides values of E_s up to 500 J cm^{-2} in a beam of ~2 cm^2. In good agreement with estimates made from the data in Fig. 5, the threshold value of E_s for LGS-E7 glass was found to be 25-26 J cm^{-2} for τ_p = 1.5 ms, about 3.2 times lower than for LGS-E1 glass. An output of 90 J was obtained with an efficiency of ~35% when E_s was above threshold by a factor of 10 and τ_p = 3.5 ms.

The efficiency may obviously be improved by careful optimization of the resonator parameters, erbium concentration and pump conditions, and decreasing the parasitic losses in EG. We also cannot forget the presence of the excited absorption of Er^{3+}, connected with the intense transition $^4I_{13/2} \rightarrow {}^4I_{9/2}$, λ_{max} = 1640 nm (Fig. 1)[18]. Its effect on the emission characteristics of ELC is equivalent to the effective value of σ_{em} diminishing to $\sigma^*_{em} = \sigma_{em} - 0.5\,\sigma_{24}$. The degree of influence of this factor does not prove to be marked.

Figure 12 shows the dependence of the gain coefficient α_{em} on E_s for various glasses measured at τ_p = 1.2 ms[20]. In both phosphate glasses, α_{em} = 0.35-0.4 cm^{-1} was obtained for which only a moderate value of E_s = 120-140 J cm^{-2}, for LGS-E7 glass, was necessary. The full gain of the discs, of thickness 3.1 cm, proved to be about 2.9-3.0 at an input energy of 2 J cm^{-2} and an amplifier aperture of 2 cm^2. It is evident that at large aperture one can take into account the parasitic influence of superfluorescence. An investigation into this factor has been carried out[21], where with τ_p = 1.5 ms an important condition for the permissible value of the disc diameter D was found to be $D_{max} \leqslant 3/\alpha_{em}$. It is correct only in the assumption that Fresnel reflection from the side faces of the AE is supressed. By using this relation, one finds $D_{max} \leqslant 10$ cm for α_{em} = 0.3 cm^{-1}. So it is possible to make effective disc amplifiers with large aperture and a high value of α_{em} with ELC.

One of the possible variations of such an amplifier module is shown in Fig. 13. 90° prisms made from glass of the same composition, activated by Er^{3+} only (N_{Er} = 5 × 10^{20} cm^{-3}), perform the beam compression and depression of parasitic emission on internal modes. They are put in deep optical contact with side facets of a rectangular erbium AE. Different quasi coaxial schemes of pumping some AE's with a single NL and many-cascade amplifiers are also possible.

Applications of erbium lasers

At the present time we believe EL's are not widely used, but their potential applications are wide and diverse. One of the expected applications[23] is the use of ELC for the development of multi-cascade amplifiers of high power short and ultra-short pulses for scientific and applied research[32-34]. It is known (see Ref. 34, for example) that a radical way of combating small-scale self-focusing, which limits the available radiance and top optical loading of the AE, involves decreasing the length of the active medium in amplifying cascades because of the increased α_{em}. The ELC makes this method possible[18,23]. Calculations[22] show that even for pulses with τ_{em} = 200 ps it is possible to make a channel with 10 amplifiers with l_p = 2 cm (one cascade) and a total gain of about 100, in which distortions of the wave-front are less than the permissible level at maximum possible efficiency ($\geqslant$ 0.2%). At $\tau_{em} \geqslant 1$ ns, when the breakdown threshold rises, the efficiency of such an amplifier can be improved by up to 0.5-0.6 %. Using discs of erbium glass in such systems also avoids the necessity of arranging their slope to be at the Brewster angle and the axis aberrations of the beam connected with this factor. It also allows the use of divergent beams, and the realization of multiple-pass and telescopic amplifiers. The low specific heat-emission makes it possible to raise the pulse repetition rate. It is also important that the length of the amplifying channel is shortened by up to 10 times and soft operation of NL flashtubes is achieved. Also wave distortions of the beam into the air space between discs due to ultra-violet emission of the flashtubes is reduced.

Applications of EL with more moderate energies are worthwhile where emission at 1.5 μm is required, or if shorter wave emission presents a danger to eyes[38]. The development of a set of rangefinders and locators based on EL's

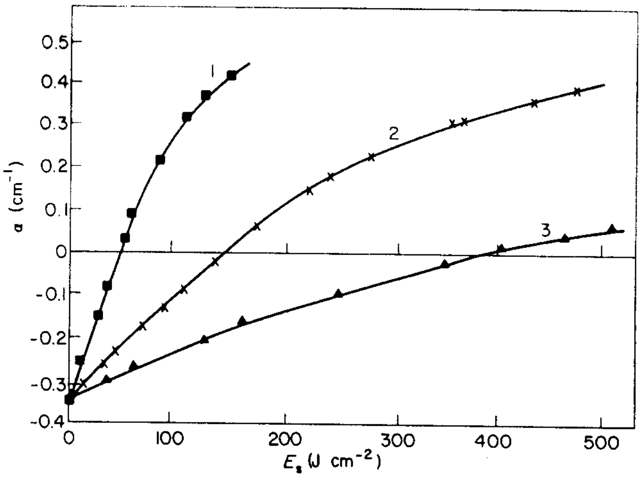

Fig. 12 Experimental gain coefficient as a function of E_s value for LGS-E7 (1), LGS-E1 (2) and silicate (3) glasses

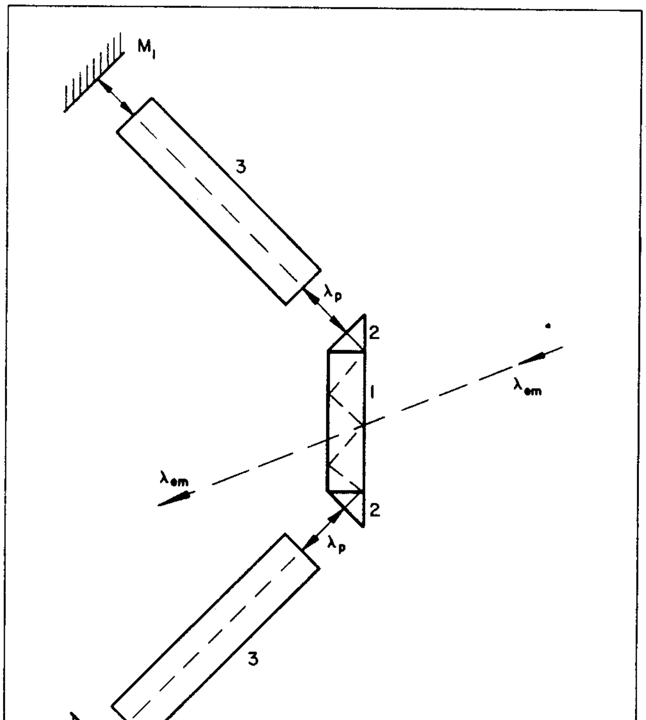

Fig. 13 Optical scheme for power amplifier cascade on base of ELC. 1 — erbium element, 2 — 90° prism of erbium glass, 3 — neodymium elements, M$_1$, M$_2$ — mirrors

has been announced[7,8,10]. It has been reported[35] that ELL, with an operating range of ~10 km, has been proposed for measuring the lower border altitude of clouds. The use of ELL in this case is tentative because of higher reflection in comparison with lidars using NL. Among other attractive fields of application are scientific investigations, for example, spectroscopy[36], laser chemistry and so on. EL's can be used as the excitation source for colour-centre lasers in the range 2-3 μm[37], or, together with NL, for parametric conversion of high power emission in the 3 μm range. Finally, use in medicine should be noted. Successful experiments treating cornea eye diseases, using ELL have already been reported[39]. Evidently EL's will also be considered in oncology and so on, because of differences in penetrative ability in tissues compared with NL and CO_2 lasers.

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