500 W XeCl – “Magic” Mark Nearly Attained

A team headed by Peter Oesterlin recently approached this goal (see Fig. 1) in an experimental set-up at Lambda Physik. The multi-hundred Watt project was supported by the German Ministry for Research and Technology. The laser is seen in Fig. 2. The laser channel and the beam output (4 cm x 5 cm) are at the small flange near the experimentalist’s head. The tank is in fact a compact wind tunnel driven by two radial fans. 4 thyatrons mounted above the tank are connected in parallel to provide energy switching. Preionization is performed by UV sparks mounted behind a mesh electrode.

The set-up is an experimental one. It will also be used in the future for applied research within the Eureka EU 205 project, the European program for the investigation of multi-kilowatt excimer lasers.

Polarized Excimer Laser Light

Frequency-narrowed excimer lasers (as EMG 150/160) emit polarized light. The broadband excimer lasers emit unpolarized light in their bandwidths given by the active excimer molecules (natural bandwidth). Sometimes there are requests to have polarized light even for emission in natural bandwidth. Such applications are:

* Experiments which need a definite photon angular momentum as in nonlinear optics, frequency conversion and stimulated scattering. Introducing an additional quarter-wave plate leads to circular polarization.

* Molecular beam experiments or experiments in low-pressure gas cells needing aligned or oriented molecular excitation, e.g. by absorbing excimer laser photons at spectral positions of incidental coincidence.

Polarization-dependent dielectric coating, it was tested firstly for one emission band, 308 nm; however, it is possible to reach similar results using coatings for 351 and 248 nm. For 193 nm, suitable coatings are not yet available.

The polarizer, which works for the 45° mounting, can be rotated around the laser beam axis to allow polarization plane rotation without beam displacement.

The degree of polarization was measured to be >100 for 130 mJ. There is no dramatic loss in total beam energy by inserting the polarizer: in the cavity configuration of Fig. 1 pulse energy rose to 140 mJ taking out the polarizer. Mounting the outcoupling mirror directly on the discharge unit (standard), energy rose to 160 mJ.

The polarizing optics will be available in summer 1988.
**Spectral Purity of a FL 3002 Dye Laser Measured with a High-Resolution Monochromator**

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**Introduction**

The pulsed tunable dye laser has proven to be a versatile tool for the experimentalist. In general, pulsed dye lasers do not emit exclusively at the selected frequency but show a spectrally broad background of spontaneous emission which is amplified by the high gain resonator (ASE). Two kinds of ASE can be distinguished: in an excimer laser-pumped dye laser, a first part is released immediately after excitation, a second part coincides with the build-up of optical feedback in the oscillator cavity. Although, due to high gain, most of the laser energy is concentrated in a narrow laser line, a low-power ASE background is always present.

The first part of the ASE can be easily suppressed by an edge filter, which consists of an oscillator and subsequent amplifiers, by an appropriate time delay in the optical excitation of the different stages. In order to suppress the second part, the Lasertechnik introduced earlier the "Lasertechnik" scheme for the FL 3002/FL 2002 dye lasers, in which the grating is used as an additional filter for the oscillator output. Recently, Klauzer [2] discussed the current Lasertechnik dye laser oscillator design and claimed that this design can produce a considerable ASE background in the central laser peak. In this paper, we investigate the spectral purity of the dye laser oscillator and subsequently the ASE background using the latest dye laser model from Lambda Physik, an FL 3002 in standard configuration.

**Experimental Methods**

The experimental set-up used in these studies is shown in Fig. 1. The FL 3002, operating with an oscillator, pre- and main amplifier was pumped by the excimer laser (EMG 1003i, Lambda Physik). A high-resolution grating monochromator (1.5 m spectrometer John Yvon, model TIR) was used to analyze the dye laser output spectrum. The spectral resolution of this monochromator was about 0.01 Å. A detection beam width of 5 Å. The dye pulses were attenuated by neutral density filters and diffused by scattering. The output of the monochromator was recorded with a photomultiplier (1P28A, RCA). The photomultiplier signals were measured with the boxcar (Stanford Research System, model SR 250) operating in the last-sample mode. The IBM PC/AT computer was connected via a 1/0 interface to the boxcar, the excimer laser and the stepper motor of the monochromator. The computer was used to control the entire experiment and to process the data from the boxcar. The stepper motor and the excimer laser were simultaneously triggered. At a fixed position of the monochromator the desired number of pulses was recorded by the boxcar and averaged by the computer. The spectra presented in the next section were obtained by averaging 10 pulses and taking the ASE background with a stepwidth of 0.08 Å. The width of the sample gate was set to 300 ms, and the laser pulse rate to 16 Hz. Rhodamine 6G in methanol was used in both the oscillator/preamplifier and amplifier dye cuvettes. All measurements were carried out at excimer laser pump energy of 100 mJ, which produced a dye laser pulse energy of about 15 mJ.

**Results and Discussion**

Fig. 2a shows the dye laser output recorded on a simple chart recorder of the FL 3002 at the maximum of the dye tuning curve (λ = 580 nm). The monochromator was about 0.01 Å. The laser beam was very strongly attenuated by the neutral density filters to avoid saturating the photomultiplier as the monochromator was scanned across the laser peak. In this recording, no satellite lines or struc-
In conclusion, a very careful and precise adjustment of the FL 3002 is recommended when an extremely high spectral purity is required.

References

Excimer Lasers in High-T\textsubscript{c} Superconductor Research

Only three years ago the scientific world was excited by the discovery of high-T\textsubscript{c} superconductors. In the mean time, an estimated 50,000 scientists and engineers work in this field so that it is difficult to get an overview on the state of the art. Excimer lasers have become important tools in the production of superconducting thin films and in the analysis of the deposition process. This article, which is not necessarily comprehensive, is an attempt to report on recent progress in this special field.

Introduction

"At the extreme forefront of research in superconductivity is the empirical search for new materials", Karl Alexander Müller and Johannes Georg Bednorz began their Nobel Prize–honoured paper in 1986 [1], referring to M. Tinkham et al., who expressed the needs at that time at a workshop at Copper Mountain, Colorado, in August of 1983.

750 W XeCl reached at Lambda Physik R & D

A few weeks ago* 750 W output were reached with the XeCl laser which had already set landmarks earlier (cf. HL 11, June 1988). Fig. 1 shows the new curve average power versus repetition rate now valid. Comparing it with that in HL 11 it is seen that the 50% higher average power is achieved by an increase of the repetition rate up to 500 Hz (300 Hz earlier). The repetition rate improvement was brought about by adding electric power. However, to take advantage of the higher electric power installed, UV preionization of the discharge had to be improved. The concept used earlier, UV emitting spark electrodes behind the mesh electrode, was given up in favor of a proprietary improved UV preionization. Dr. Elmar Müller-Horsche, head of the research team,

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* First reported at the Eureka EU 205 meeting, October 9, 1989.

Fig. 1: Average power versus repetition rate

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Why thin films?

It turned out soon that high-T\textsubscript{c} superconductivity in the bulk material suffered from low current density: if the current in a sample is increased, a breakdown of superconductivity occurs. Furthermore, since the superconductivity effect is strongly anisotropic, in a poly-crystalline bulk an unfavorable averaging of the superconducting properties of all crystal orientations occurs. On the other hand, once crystal growth is epitaxial, the supercurrent density can be increased over that of polycrystalline material. Fig. 2 [3] shows schematically the material deposited in the favorable c-orientation on a SrTiO,

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The "copper mountain" in superconductivity began to rise with Müller's and Bednorz' publication, and has apparently not yet reached its summit: Fig. 1 [2] shows what happened with respect to the transition temperature of superconductors since 1911, when Kamerlingh–Onnes discovered superconductivity in mercury. Indeed, the compound Ba–La–Cu–O opened a new era; Cu–O was soon recognized to form a non–perovskite type phase of that compound responsible for superconductivity (as firstly communicated in a note added in proof in [1]).

Within a few months after the publication of [1], the transition temperature rose to 92 K, as achieved at the University of Houston (C.W. Chu and co-workers, 1987) by replacing lanthanum with the smaller yttrium ion. The importance of this result: the transition temperature was then raised to above 77 K, which is the temperature of liquid nitrogen at atmospheric pressure.

YBa\textsubscript{2}Cu\textsubscript{4}O\textsubscript{6} became the high-T\textsubscript{c} compound mainly investigated until today, frequently called "one-two-three" for the stoichiometry of the first three atoms. "x" stands for a variable deficiency of oxygen. In other laboratories in Japan and the US. bismuth and thallium cuprates have been found meanwhile to exhibit even higher transition temperatures. and, following the opinion of experts, a definite end of this development is not yet to be seen.

The role of lasers in the game is twofold. Laser evaporation is very effective, very reliable, and fairly simple in the deposition of thin films of said superconductors. Furthermore, laser induced fluorescence is a convenient means to analyze molecular composition and details of the deposition kinetics.

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Lambda Highlights N°19/20

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* First reported at the Eureka EU 205 meeting, October 9, 1989.

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foresees further increase of average power of this type of laser using X-ray photoemission. To reach 1 kW is the goal of the second phase of the Eureka EU 205 project which is to start in 1990. Clearly, although under laboratory conditions, realizing average power in this order of magnitude provides a lot of experience for current product development, especially as the materials employed undergo rigorous testing. In addition, UV preionization, which is less costly than the X-ray technique, shows remarkable potential for medium to high-power lasers. Fig. 2 shows the laser in a view somewhat different from that in HL 8.

... Superconductors

crystal, superconductors supposedly flowing in the Cu-O planes which extend parallel to the substrate. In addition, from a practical point of view, this film is the usual approach to designing advanced electronic circuits. This holds even more so as the production of superconducting wires raises problems, since the material is very brittle. However, thin films need convenient substrates. To achieve epitaxial films, ideally the substrate should show a crystalline lattice favorable for the film to arrange. This is the reason that Si/Ge, is frequently chosen as the substrate for experimental investigation. However, for any practical application in electronics circuits, Si would be much more convenient as the substrate.

Depositing thin films

Producing thin films of multi-element composition can be performed by simultaneous vapor or molecular beam deposition using e.g. three different ovens (HL 7). Generally, this trend has been questioned again recently, this trend has been questioned again. Also metal-organic vapor deposition is used. These procedures are difficult to control and costly. Therefore, the superconducting compounds are mixed in advance in an almost correct stoichiometric ratio. Targets prepared in this way are then sputtered onto a substrate. Also, flash-evaporation of the pretested material was tried. The difficulty is maintaining the stoichiometric ratio during evaporation. Another well-known deposition technique is magnetron sputtering.

The aim of any deposition technique for high-Tc films is to obtain the required stoichiometry in the film including the oxygen content, to achieve almost undirectional growth in the required crystalline structure, and to avoid impurities. Frequently, these goals cannot be achieved simultaneously so that an annealing process of the as-deposited film in oxygen may be necessary.

Depositing high-Tc layers: annealing or not?

Excimer laser ablation was firstly used at Bellcore by Yavasovian et al., as Highlights reported in its October 1987 issue (HL 7). Generally, pulsed laser radiation can be applied in a well-controllable way to the target. Pulsed UV radiation is very effective in the ablation of non-volatile and ceramic materials. As a consequence, in the film, almost the same stoichiometry as in the bulk can be achieved. However, as reported by the Bellocre group in 1988 [8], cooling down over several hours was still necessary. Heating of the substrate during deposition was required providing thermal energy for the deposited atoms and molecules to migrate on the surface and to arrange themselves in the energetically favorable lattice. Post-deposition annealing is not only time-consuming for any practical application. Also, high-temperature annealing favors interdiffusion from the target to the superconductor, thus spoiling the superconducting properties of the film. Due to the careful control of the deposition process film situation has now changed dramatically, as will be described below.

A recent magnetron sputtering experiment should be mentioned [4] it allowed a moderate temperature (645°C) at the substrate, and did not require annealing, but a careful cooling-down at a rate of 30 K/min. Critical current density was 2 x 10^4 A/cm^2 at 77 K which is not as high as that reached by the laser techniques.

UV wavelengths are favorable

Infrared lasers have also been applied for laser evaporation. Recently, films close to the stoichiometry of the target were obtained [5] using a long-pulse (about 1 ms) 50 J Nd:glass laser, providing a fast deposition rate (100 nm/pulse); however, 850°C annealing was still necessary. Deposition by frequency-doubled short-pulse (10 ns) Nd:YAG laser radiation, 352 nm, required 725°C at the substrate [6]; the same group reports that frequency-tripled radiation (335 nm) produces much smoother films [6]. A similar result is reported in [12]. Obviously, Nd:YAG laser users recognized that short wavelengths are more favorable. In principle, this would not be surprising, considering the background of excellent metals material processing capabilities demonstrated in many laboratories for excimer lasers. However, very recently, this trend has been questioned again by a paper published by the same IBM group [7], who reports that in situ layers epitaxially grown on LiNbO3 do not show superconducting properties different when deposited using Nd:YAG fundamental, frequency-doubled or tripled radiation.

Excimer-laser deposition: defining the process parameters

Avoiding post-deposition annealing

First results in producing excimer laser-deposited 1-2-3 layers in situ without annealing were reported in HL 7. In these early experiments annealing in oxygen at 900°C and
they improved their technique by applying an oxygen jet directly to the substrate and observed chemiluminescence when the plasma of laser-ablated atoms appeared apparently, neutralizing of metal atoms occurred already in the gas phase. In this way, in-situ films of about 200 Å thickness on SrTiO$_3$ and Al$_2$O$_3$, superconducting as-deposited, could be achieved, needing fairly low substrate temperatures of 50°C and 580°C. Cooling down at 250 Torr oxygen pressure took about 1 h. A short time later, a Siemens group also succeeded in circumventing annealing. However, the substrate temperature was still high (750°C) and, again, cooling down as long as 1 h was necessary [8]. It was soon recognized that lengthy post-deposition annealing could be avoided by using moderate substrate temperatures only, having appropriate oxygen admission or by switching off the heater as early as possible after deposition: A typical set-up for laser deposition is shown in fig. 2 as realized by B. Stüttz and co-workers at RFA Jülich, PGO [10]. They use a 248nm excimer laser (LFK), slightly focusing the beam. As will be described below, only a few femtoseconds are necessary to obtain good results. As reported also by other groups, the repetition rate has to be in the range of 5 to 10 Hz, otherwise the films do not grow in the required crystallographic structure. Due to the short wavelength, spatially, as well as ambient gas is excited to fluorescence or chemiluminescence (fig. 4) (compare also HIL 7). In a recent experiment [11], Pettlingsdorf, Zander, and Stüttzach achieved $50 \times 10^9$ atoms appeared: a particular current of $5.2 \times 10^6$ A/cm$^2$ was sustained already. The cleaning of metal atoms and oxygen is very essential [9].

### The deposition temperature

In this experiment, the deposition temperature was found to be fairly critical. Fig. 5a shows the optimal transition into superconductivity (a) achieved in this experiment, and (b) a plot demonstrating the importance of a careful choice of the substrate temperature in order to achieve a narrow transition width; the T$_c$ onset (R=0.1%) temperature is plotted against substrate temperature as well as temperatures below by fractional resistivities including R=0. Clearly, at 780°C the curves mostly approach each other, showing that the transition from ohmic resistance (100%) to superconductivity (R=0) is very steep at this temperature when the substrate has been chosen. The transition width (defined as the 10%–90% resistance interval) is 1K only. It should be mentioned here that the resistance curves are generally measured with the standard four-probe technique, the critical current densities up to which superconductivity survivals are obtained by applying increasing current through a well defined bridge in the film (suitably prepared by excimer laser ablation) and measuring the voltage/current characteristics until ohmic behaviour appears.

### Congruent evaporation: dependence on fluence

The dependence of the film composition on laser pulse fluences for a given laser-target combination was systematically investigated by Roas, Schütz, and Endres [12] of Siemens, Erlangen, using a 106 J/cm$^2$ laser. Fig. 5b shows a triangular at-% composition diagram for Y-Ba-Cu. To draw this diagram, start at a point within the triangle, projecting a line parallel to the Ba axis to find the copper percentage. Then rotate counterclockwise until parallel to the Y axis in order to find the Ba %, then parallel to the Cu axis to find the Y %. The ideal 1:2:3 stoichiometry is given by the intersection of the three lines (verify the 50:33:33, 16.6% ratio). The experimental points, for different fluences, refer to the compositions found on the film (as determined by x-ray), and, correspondingly, on the target at the spot after laser deposition. Clearly, the circles (4.5 at%) and the triangles correspond to the target composition (full circles) and film (open) close to 1:2:3 stoichiometry indicating the most congruent evaporation at this fluence. Fortunately, fluctuations in this order of magnitude are easily achieved by current excimer lasers. The layers obtained in this way were found to be grown epitaxially (on SrTiO$_3$) with excellent superconducting properites: critical current was measured in 5.2 x 10$^{10}$ A/cm$^2$ at 77 K, at 2 Tesla still being 3 x 10$^{10}$ A/cm$^2$. Also, at 4 K, where classical superconductor's week, superconductivity up to a current density of 10$^{10}$ A/cm$^2$ was found, about an order of magnitude higher than that of commercial deposits, the authors report.
are believed to enhance the oxygen content of the deposited films, thus improving its superconducting properties. Very recently, Bormann and Nolting [15] pointed out that favorable O2 conditions are in accordance with the O2 vapor pressure of the material in dependence of temperature.

Homogeneous velocity of atoms in superionic beams

In a recent publication by the Buffalo group [16] the influence of the oxygen background on the velocity distribution of the target atoms released by the laser pulses was investigated in more detail. Using an optical time-of-flight method (TOF) (see Fig. 8) to analyze the velocity distribution of individual species in the plasma plume at 10 Torr background pressure, the distributions of Cs, Y, and Ba atoms were measured (assuming that TOF spectra were independent of the atom’s emission line monitored) at a distance of 7.2 cm from the target. The distributions, averaged over 200 laser shots, could be fitted almost perfectly with a distribution to be obtained in an isostropic superionic beam expansion. Thus, considerable energy and speed was transferred to the atoms:

Table 1: Superionic expansion parameters obtained in ArF laser-generated ablation with 5.3 J/cm², focused to a spot of 0.5 x 1.1 mm²

<table>
<thead>
<tr>
<th>Species</th>
<th>Most probable speed (10⁻⁷ m/s)</th>
<th>Mean kinetic energy (eV)</th>
<th>Mach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca I</td>
<td>1.97</td>
<td>4.05</td>
<td>4.35</td>
</tr>
<tr>
<td>Y I</td>
<td>1.2</td>
<td>4.43</td>
<td>4.30</td>
</tr>
<tr>
<td>Ba I</td>
<td>0.82</td>
<td>2.3</td>
<td>4.72</td>
</tr>
<tr>
<td>Ba II</td>
<td>1.1</td>
<td>2.3</td>
<td>8.46</td>
</tr>
</tbody>
</table>

The remarkable result is that a superionic molecular beam is formed, very similar to beams obtained in hydrodynamic expansion of a fairly high-pressure gas via a nozzle, and that the most probable velocity values do not differ so much, by less than a factor of 2, by the hydrodynamic expansion. In an accompanying paper [17], the influence of the oxygen flow onto the velocity distribution of the superionic beam was calculated. (Lattice structure analysis. See also Fig. 9.) Again, an EMG ArF laser was used to collimate the beam via the oxygen jet on to the target, providing afluence of 5.3 J/cm² which was found most convenient for the generation of superconducting films. The oxygen jet was observed to emit a red glow indicating efficient interaction of the 193 nm radiation with O2 molecules. A DC voltage was applied downstream to enhance the discharge of the ions and large charges, thus producing a sub-atmospheric pressure to enhance the oxygen partial pressure. A high oxygen partial pressure is essential for the production of higher-quality superconducting films.

“Tailored” films of Bi-Sr-Ca-Oxides by excimer laser ablation: Higher Tc by lattice engineering?

As already mentioned at the beginning of this article, higher Tc values were observed, e.g. in Bi-Sr-Ca-Cu-Oxides (BSCCO) [20] which appeared to contain two superconducting phases with Tc's at 85 K and 105-115 K [21]. Clearly, to analyze the site of superconducting phases and the influence of the constituents on the film is a major challenge. Investigations focused to this aspect are being done at Osaka University, Japan, by the group of Professor Kawai using an EMG ArF excimer laser [22]. In order to control the deposition of multilayer films, the researchers used several targets ["multitarget"] exposing to sequentially from a N2 O gas atmosphere in the oxidizer. Targets were intermixed disks of Bi2O3, CuO, SrO, CaO, CuO, and Y2O3. Irradiation was performed in a sequential operation as to form 300 A thick layers of different compositions in which Sr atoms were partly replaced by metallic Ba and Sr-Ca-Cu-O films on Si were presented by Krebs and Kohlbeck [24], using an LPX 1100 they produced films showing superconducting properties. Also, applying oxygen in a narrow pressure range in agreement with [15]. In this case, the collapse of superconducting (or non-superconducting) properties. E.g. Fig. 3 shows lattices with different numbers of CuO layers between the BiO layers which were obtained at low substrate temperature and reaction with N2O. Clearly, these investigations are in an early stage. However, even if no industrial application would emerge – due to complexity of the process or other restrictions – the results obtained for understanding of the high-Tc phenomenon are most important.

Resume: High-tech pushes high-tech

This short survey of the work going on with Bi-Sr-Ca-Oxides and other compounds is by no means complete. Tremendous efforts are being made around the world to develop the processing parameters and to correlate them with good results for high-Tc films. Obviously, most parameters are interdependent so that comparisons are somewhat difficult. However, as a step forward the results as a whole, a preliminary view arises.

- Stoichiometry is most critically essential with respect to the oxygen content.
- Epitaxially grown films in single phase are most important.
- Reproducible production is to be guaranteed.
- Long-term stability has to be guaranteed.
- Lattice structures leading to higher Tc should be explored.

All the different experimental attempts discussed here have these goals in mind. Whichever technique will prove best is presently open. This is certainly also true for techniques competing with laser ablation methods.

For a technical application in electronic circuits, deposition of high-Tc films on Si or other semiconductor materials as well as the incorporation of metallic conductors will be most important. In this respect research is at the early beginning. The first results of in-situ preparation of c-axis oriented Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O films on Si were presented by Krebs and Kohlbeck [24], using an LPX 1100 they produced films showing superconducting properties. Also, applying oxygen in a narrow pressure range in agreement with [15]. In this case, the collapse of superconducting (or non-superconducting) properties. E.g. Fig. 3 shows lattices with different numbers of CuO layers between the BiO layers which were obtained at low substrate temperature and reaction with N2O. Clearly, these investigations are in an early stage. However, even if no industrial application would emerge – due to complexity of the process or other restrictions – the results obtained for understanding of the high-Tc phenomenon are most important.

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Chinese Scientist guest at Lambda Physik R & D

Zhang Yuchuan, Senior Engineer and Deputy Director at the Beijing Institute of Opto-Electronic Technology, Beijing, Peoples Republic of China, was at Lambda Physik for 11 months, working at the R & D division in Göttingen. His stay was a good example for the fruitful cooperation possible across borders which, until recently, were believed to be unsurmountable for a long time. At his Institute he mostly fulfilled management functions, so he enjoyed laboratory work, having sufficient time to do practical things. For example, using a laboratory set-up, he investigated the excimer laser beam pattern under various conditions, extending the analysis to the farfield pattern. Such time-consuming measurements are important for laser application and instrument improvement.

In 1977 Zhang Yuchuan first took notice of Lambda Physik, still in the "nitrogen laser era", when he investigated at his university a nitrogen laser he had built himself. At that time, Dirk Basting visited that laboratory so that the personal contact came about. Zhang Yuchuan took advantage of his stay travelling through different parts of Germany. When asked what he liked the most he appreciated very much Göttingen, “the city is so quiet – in comparison to the densely-populated big Chinese cities”. In this respect, Munich seemed to him more comparable to Shanghai!

He noted a high efficiency in the daily work, and he was especially impressed by the skill of the technicians working at Lambda Physik. On coming home, he intends to apply his new experiences, as much as possible, to his work at the Institute. However, first of all, he looked forward to seeing his family again.

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Influence of hydrogen on the characteristics of an excimer XeCl* laser

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The characteristics of an electric-discharge XeCl* laser were improved by the addition of hydrogen to an He–Xe–HCl mixture. The energy of the output radiation pulses increased by 15% and the operation of the laser became stabilized. A study was made of the dependence of the output energy on the hydrogen concentration.

Beginning from the seventies the popularity of excimer lasers as effective sources of visible and ultraviolet radiation has increased. The best characteristics among excimer lasers have been reported for rare-gas halides KrF*, XeCl, etc. Further forced energy deposition in the medium is causing difficulties, so that it would be highly desirable to consider improvement of the excimer laser characteristics by optimization of the composition of the gas mixture.

The present paper reports an increase in the efficiency of an electric-discharge XeCl* laser on addition of hydrogen to an He–Xe–HCl mixture. We shall give the dependence of the output energy of the laser on the hydrogen concentration.

The active medium was excited by a transverse discharge preceded by ultraviolet preionization. The electrical part of the apparatus was in the form of the circuit shown in Fig. 1. A storage capacitor C0 consisted of three K-15-10 capacitors connected in parallel and 10 nF each. A high-pressure spark gap G was used to switch on the discharge. The dimensions of the main discharge gap were 60 × 0.5 × 2 cm (where 2 cm was the distance between the electrodes). The voltage across the electrodes was \( U = 18 \) kV, the duration of the discharge at midamplitude was \( \tau_d \approx 50 \) ns, the duration of the laser output pulses was \( \tau_I \approx 30 \) ns. The output energy was measured with a IKT-1M calorimeter and the duration of the output pulses was determined with an FK-22 photocathode.

Preliminary ionization of the medium was provided by a discharge on the surface of an insulator. The preionization system was located axially along the electrodes. The discharge on the insulator surface was characterized by a high spectral brightness in the short-wavelength range, which ensured effective preionization of the gas mixture.

The influence of the addition of hydrogen on the output characteristics of the laser was investigated as follows: first, the composition of the He–Xe–HCl mixture was optimized in respect of the output energy. It was found that when this composition was He:Xe:HCl = 1000:10:1, the energy reached 21 mJ, which corresponded to an efficiency of \( \eta = 1.5\% \) relative to the stored energy. Then, hydrogen was added to this optimized He–Xe–HCl mixture. The dependence of the output energy on the hydrogen concentration was determined (Fig. 2). In the case of a mixture with the He:Xe:HCl = 1000:10:1 composition the energy of the radiation pulse is increased by 15% reaching 25 mJ; moreover, the stability of operation of the laser improved. Lasing occurred at wavelengths \( \lambda_f = 307.87 \) and \( \lambda_s = 308.0 \) nm. An improvement in the reproducibility of the energy from one pulse to another was clearly due to recovery of the HCl molecule by the reaction

\[
\text{H}_2 + \text{Cl}_2 = 2\text{HCl.} \tag{1}
\]

Since an increase in the energy deposited in the mixture resulted in a practically linear increase in the output energy, it was concluded that the HCl donor was not significantly “depleted” during one pulse. Therefore, the increase in the energy of the first pulses in the series could not be explained by the reaction (1). The improvement in the output characteristics of the laser was clearly due to the following factors:

1) cooling of electrons due to excitation of vibrations of the \( \text{H}_2 \) molecule:

\[
\text{H}_2 + e \rightarrow \text{H}_2(\nu) + e, \tag{2}
\]

which increased the rate of excitation of vibrations of the HCl molecule in accordance with the reaction

\[
\text{HCl} + e \rightarrow \text{HCl}(\nu) + e; \tag{3}
\]

2) transfer of the vibrational excitation from the molecules

\[
\text{H}_2(\nu) + \text{HCl} \rightarrow \text{HCl}(\nu) + \text{H}_2.
\]

Therefore, when hydrogen was added to the He–Xe–HCl mixture, there was an effective increase in the

**FIG. 1.** Electrical part of the apparatus: \( R_1 \) and \( R_2 \) are resistors in the charging circuit; \( C_0 \) is a storage capacitor; \( G \) is a discharge gap; \( C_1 \) is a peaking capacitor; \( C_2 \) is a decoupling capacitor in the preionization circuit; \( C_3 \) and \( C_4 \) are capacitors in the voltage divider circuit; TR is the current transformer.

**FIG. 2.** Dependence of the output energy on \( \alpha = [\text{H}_2]/[\text{HCl}] \) for a mixture of the He:Xe:HCl = 1000:10:1 composition with \( [\text{He}] = 8 \times 10^{14} \text{ cm}^{-3} \).
Lasing due to impurity color centers in yttrium aluminum garnet crystals at wavelengths in the range 1.35–1.45 μm

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Low-threshold wide-band lasing was achieved for a YAG crystal with optically and thermally stable color centers. The absorption and luminescence spectra were determined, and the gain was measured in the range of wavelengths corresponding to the color-center luminescence. The cross section of the lasing transition was estimated (8 × 10⁻¹⁹ cm²) and the efficiency of conversion of the pump radiation from a neodymium laser into the output radiation was determined (10%).

Solid-state tunable lasers operating in the near infrared have some important applications. Much of the work on these lasers has been concerned with the spectral and lasing characteristics of crystalline materials doped with transition-metal ions V²⁺, Ni²⁺, and Co²⁺ and with lasers made using these materials and emitting in the range 1.2–1.8 μm (Ref. 1). However, lasers of this type are not used widely because the active medium has to be cooled to cryogenic temperatures. Considerable progress has recently been made on the construction of color-center lasers using alkali halide crystals, which can operate efficiently at room temperature.² Unfortunately, the instability of the parameters of active elements of lasers of this type under the influence of elevated temperatures or of ultraviolet and visible optical radiation limits seriously the potential applications of these lasers.

We shall report lasing observed in the range 1.35–1.45 μm for optically and thermally stable impurity color centers in yttrium aluminum garnet (YAG) crystals. Impurity color centers in crystals with the garnet structure can be formed by doping with chromium and oxidation of this impurity to the quadrivalent state. These color centers have strong absorption bands in the visible and near-infrared parts of the spectrum. Figure 1 shows the absorption spectrum recorded at 300 K for a YAG crystal containing color centers. Excitation of such a crystal in the absorption band of the color centers produced luminescence in the wavelength range 1.25–1.7 μm, the spectrum of which is shown in Fig. 2. The luminescence decay kinetics observed on pulsed excitation of the color centers with a Q-switched and neodymium laser was exponential with a time constant 4.6 μs at 300 K. Bleaching of the crystals with color centers was observed in a band at 9000–12 000 cm⁻¹ when they were subjected to the same neodymium laser radiation and the density of the absorbed energy was ~40 mJ/cm², which indicated that a population inversion was attained for the main transition in the color centers. Bleaching of YAG crystals with color centers in the absorption band at moderate densities of the absorbed energy and the wide spectrum of the color-center lumines-

FIG. 1. Absorption spectrum of a YAG crystal with color centers.
R6A  R590
Lots made up
Look up in PDL manual
cone 0.5  5/1000

\( \frac{1}{2} \) liter

In draw
R6A in frig

Glass jar methanol if possible