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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking General Physics Institute as follows: The contractor will investigate non-thermal lens formation in LiF:F2- lasers and, based on an understanding of that lens formation process, develop a concept for a laser, including the pump source and the resonator, for producing 10 to 40 watts of power at 589 nm.

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Laser with Wavelength 0.589 μm ("Sodium Wavelength Laser")

Final report

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Moscow
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Below we discuss the next questions.

1. Non thermal lens formation in LiF:F_2^- active element.
2. LiF:F_2^- laser resonator configuration.
3. Low threshold pump power experiment.
4. Mode-locked LiF:F_2^- laser.
5. Heating of LiF:F_2^- crystal under pump and laser radiation.
6. Estimation of pump YAG:Nd laser power and output LiF: F_2^- laser power needed to obtain 10- 50 W at 589 nm
7. LiF:F_2^- laser system with SHG with output power up to 50 W at 589 nm

1. Non thermal lens formation

Non thermal lens formation under action of pump radiation in a LiF: F_2^- crystal has been observed earlier [1]. It is rather difficult task to measure the lens formation because dimension of pump beam inside LiF is rather small (200 - 300 μm). But there are articles in literature in which similar problem has been studied. In [2] TEM_{00} mode formation and its stability in resonators with radial gain profile has been studied both theoretically and experimentally. Authors of this paper have come to conclusion that "for sufficiently high quadratic gain $\alpha 2$ the beam radius (and radius of curvature) are essentially independent of the mirrors' curvatures and separation", in other words parameters of TEM_{00} mode essentially depend on gain diameter and weakly depend on resonator parameters. In this paper gain media was distributed along laser resonator. In our case LiF laser resonator is long in comparison with length of LiF crystal (for example the crystal length is 2.5 cm, resonator length is 13 - 100 cm). In [3] it was shown that the similar result takes place for resonator with mirrors which have Gaussian reflectivity. Having this considerations in mind we suppose that in our case gain profile bring about TEM_{00} mode formation and experimentally it looks like as there is lens in the crystal. This does not exclude that there is not any lens in the crystal, more over, there should to be lens indeed and we see summary manifestation of all these factors. But in any case for our purposes we have to find LiF laser resonator configuration which is insensitive to lens in the crystal.

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2. Resonator configuration

Here we discuss too possible resonator configuration. One resonator configuration is presented in Fig.1a. We will refer to this configuration as "short" resonator. "Short" resonator consists of two mirrors with equal radii of curvature r_1=r_2. Resonator length d is close to d= r_1+r_2, LiF crystal is placed in the middle of the resonator. TEM_{00} – mode diameter inside LiF active element was chosen as criteria of resonator "quality" because output power and divergence of radiation of LiF:F_2^- laser strongly depend on this diameter. Results of calculation TEM_{00} - mode diameter (4w) are presented in Fig. 2a for three values of the lens focal length in the LiF crystal: f_1= ∞, +5 cm and -5 cm. It is assumed that lens in the crystal is due to parabolic transverse index distribution and this distribution does not depend on co-ordinate along resonator. Parameters of the resonator are d=13 cm, r_1=r_2=6.5 cm, LiF: F_2^- crystal length l=2.5 cm. One can clear see that the mode diameter in the LiF: F_2^- crystal is insensitive to the value of lens focal length and its value at waist is about 320 μm. This resonator configuration has a disadvantage. It is too short and there is not enough room for a spectral selection element.

Another scheme of the LiF: F_2^- laser resonator is presented in Fig. 1b. It has been found the radii of curvature of mirrors, focal length of lens and distances between the elements for this resonator configuration for which mode diameter in LiF weakly depends on lens focal length in LiF. There are results of calculation of TEM_{00} - mode diameter in LiF in Fig. 2b. Mirror (1) radius of curvature is 6.5 cm; radius of curvature of mirror (4) is 500 cm; lens (3) focal length is 20 cm, and l_1=6.1 cm, l_2=27 cm, d=250 cm. Calculations were made for three cases of lens focal length inside the active element 2 (see Fig. 1b) ∞, +5 cm, and -5 cm. One can see from Fig. 2b that this resonator configuration has low sensitivity to the lens focal length inside the active element. The diameter of TEM_{00} - mode inside the LiF is about 300 μm. This value is close to the previous one for the "short" resonator, so we can expect that values of pump power thresholds for these two configurations have to be close to each other.

Now let us discuss how the TEM_{00} - mode parameters change when distances l_2 differ from assumed in the previous calculation. This is important from point of view experimental realisation of this resonator configuration. In Fig. 3 there are diameters of TEM_{00} - mode in the middle LiF active element as function of distance between mirror 1 (see Fig. 1b) and lens 3 at fixed length of laser resonator. Three curves in Fig. 3 are correspondent to the lens focal lengths in an active element ∞, +5 cm, and -5 cm. One can see from the picture that the diameter changes from 250 μm to 350 μm when l_2 is in the range 26 cm ÷ 28 cm. This range is not wide but it is acceptable for experimental realisation.

3. Low threshold pump power experiment

The pump YAG:Nd laser had negative feedback electronic loop enabling the laser to emit spikes-free 80 μs pulses. The LiF:F_2^- laser scheme is presented in Fig. 1a. The LiF:F_2^- active element length was 2.5 cm and had initial transmission T_0=39%, transmission at high power T_1=75% (transmission at wavelength of generation T_2=83%), output mirror reflectivity was about 95% at wavelength of generation. The collinear scheme of pumping was implemented. Pulse repetition rate was up to 5 Hz, so average pump power was low and it is possible do not take into account thermal lens in LiF:F_2^- crystal.

Fig. 4 (*a*) shows pump power at the incidence plane of LiF:F_2^- crystal as function of time. Output power of the LiF:F_2^- laser (λ=1.19 μm) versus time is presented in Fig. 4 (*b*). The traces in Fig. 4 were obtained with a digital oscilloscope TDS 744A and photodiode LFD -2a with time resolution about 1 ns. Vertical axes in Fig. 4 are calibrated in Watts.

To find the value of threshold, we have calculated output power P as function of pump power P_p by using expression $P(\eta, P_P, P_1) = \eta \cdot P_P - P_1$, ($P(\eta, P_P, P_1) \geq 0$), where η is the slope efficiency. The parameters η and P_1 have been found by minimising the function $F(\eta, P_1) = \sum_i (P_{0i} - P(\eta, P_{Pi}, P_1))^2$, where P_{0i} and P_{Pi} are the experimentally measured output and pump powers and index *i* runs from 1 to 500 (see Fig. 4). The calculations have showed that $F(\eta, P_1)$ has minimum at η=5.7% and P_1=0.46W. In Fig. 4*b*, the dashed curve is calculated one with these values η, P_1. So it is possible to calculate the threshold value $P_{th}=P_1/\eta$, which is occurred to be 8.2W.

The LiF: F_2^- laser resonator configuration that is presented in Fig. 1b has been tested too. Parameters of the laser resonator are: mirror (1), radius of curvature 6.5 cm, transmission at wavelength 1.064 μm - 70 %, reflectivity at wavelength 1.18 μm - 99 %; LiF: F_2^- crystal (2) initial transmission T_0=39%, transmission at high power T_1=75% (1.064 μm), transmission at wavelength of generation T_2=83%, lens (3) focal length +20 cm, AR coated at 1.18 μm; mirror (4), radius of curvature 500 cm, reflectivity at wavelength 1.18 μm - 90 %. Pump beam is passing through mirror (1). It was found that threshold was about 5 – 8 W. This value is close to one for the "short" resonator.

4. Mode-locked LiF:F_2^- laser

To obtain mode-locked LiF:F_2^- laser oscillation we developed mode-locked YAG:Nd laser, which was used as pump source. The YAG:Nd laser had both negative feedback and active mode locking. Optical scheme of the laser is presented in Fig. 5: 1 and 6 - resonator mirrors, 2 - YAG:Nd rod, 3 - glass plane-parallel plate, 4 - Glan prism, 5 – electrooptical modulator (EOM), 7 – photodiode (PD) for negative feedback. The photodiode and an electronic scheme, which ensure negative feedback, were situated as close to EOM as possible. PD is illuminated by light reflected by plate 3 and guided by optical fibre 8; lens 9 collected the light on the input face of the fibre. Length of the laser resonator was 235 cm, optical length - about 250 cm.

There is the electric scheme in Fig. 6. High frequency transistor T1 (KT-922A) was served to change the voltage which was applied to EOM. Photodiode PD1 (p-i-n, type LFD-2a) was used to modulate the current passing through the transistor. Capacitance of the EOM is C2=80 pF, r1=2 kΩ, r4=91 Ω, resistors r2 and r3 serve to choose the working point of the transistor, DC voltage U_0=40 V. Voltage U applied to EOM was about 3.5 V lower, because constant current 40 mA passed through the transistor. EOM $U_{\lambda/2}$ voltage was about 400 V at wavelength 1.06 μm. In our case the EOM was aligned so that its transmission (transmission when light is passing through Glan prism 4 - EOM 5 - mirror 6 - EOM 5 - Glan prism 4, see Fig. 5) at U=0 was lower than at U=40 V. High frequency (f=59690 kHz) signal was applied to resistor r1 to reach mode-locking laser generation regime.

The electric scheme is operating in the next way. When there is no signal from photodiode PD1 almost 40 V is applied to EOM and losses inside the laser resonator due to Glan prism and EOM are low. When laser threshold is achieved (under action of flashlamp pumping) generation begins and laser light illuminates photodiode PD1. Electric signal from the photodiode opens the transistor T1 and voltage at EOM becomes lower and the losses inside the laser resonator higher. This is negative feedback because the higher laser intensity the higher losses due to EOM inside the laser resonator which leads therefore to lowering of generation intensity. Thus spikes are damped and shape of laser pulse becomes smooth. HF - signal modulates current of the transistor T1 (see Fig. 6) so that voltage at the EOM alternates with the same frequency. The voltage at EOM due to negative feedback is shown in Fig. 7: a - without HF-signal, b - HF-signal is applied.

There is output intensity of laser generation as function of time in Fig. 8. Output consists of a long (about 80 μs, see Fig. 8a) train of short (about 1.5 - 2 ns, see Fig. 8b) pulses, energy of the train is 2 mJ. The signals were obtained by using photodiode LFD-2a (time resolution about 1 ns) and oscilloscope TEKTRONIX 7104 (bandwidth 1 GHz).

YAG:Nd laser described above was implemented to pump LiF: F_2^- laser. Scheme of LiF: F_2^- laser is shown in Fig. 1b. Mirror 1 radius of curvature is 6.5 cm, reflectivity at wavelength 1.178 μm is 99 %, transmission at wavelength 1.064 μm is about 70 %, for mirror 4 these parameters are 500 cm, 90 %, 5 % accordingly. AR coated lens 3 focal length is 20 cm, l_1=6.1 cm, l_2=27 cm, d=250 cm. The length of the YAG:Nd laser resonator was equal to one of the LiF: F_2^- laser. To reduce feedback between these two resonators λ/4 plate were employed at output of neodymium laser. Pump power threshold of LiF:F_2^- laser was less then 8 W. In Fig. 9 there are oscilloscope traces of LiF: F_2^- laser at 5 ns/div (a) and 5 μs/div (b). Short pulse duration was about 2 ns, full duration was about 50 μs.

5. Heating of LiF: F_2^- crystal under pump and laser radiation

Here we evaluate temperature distribution in rotating LiF:F_2^- laser crystal which has form of a tube. Let an inner diameter of the tube to be R_1 and outer one R_2, denote $x_0=(R_2-R_1)/2$ and let $x_0<<R_1$, R_2, let also the length of the crystal to be L. There is scheme of LiF:F_2^- laser crystal and parts of construction in Fig. 10. The heat generated inside the crystal is taking away via gaps filled with a gas to bulk metal. These metal parts of the system are cooled by water or by some thermoelectric element but in any case technically it is possible to keep needed temperature of this part. Let us assume also that heat flux is constant on the surface of the crystal.

Evaluate temperature step (jump) δT on boundaries of the gaps, which is needed to ensure withdraw heat power P_t that is generated inside the crystal. If the gap thickens is l, thermal conductivity of the gas is χ, surface area $s=2\pi R_1 L$, then $\delta T=P_t\, l/2s\chi$. Thermal conductivity for some gases is χ= 2.57 10^{-4} W/cm K (N_2, 300 K), and χ=12.2 10^{-4} W/cm K (He, 300 K) [4], for l=0.2 mm, s=66 cm^2 ($2R_1\approx 2R_2$ =7 cm, L=3 cm) and P_t=100 W we have δT=59 K (N_2), δT=10 K (He). One can see that it is possible to ensure cooling of the crystal in He atmosphere ($P_t\leq$100 W) and if the bulk metal is cooled 10 K below room temperature, the surface of the crystal will have room temperature.

Temperature distribution in the LiF: F_2^- crystal.

When the LiF: F_2^- crystal is revolving pump (and generation) beam draw something like line on the input and output faces of the crystal. Let us assume that thickens of the line is 2h, and the line is positioned at half distance between sides of the tube. So the heat is generated in a volume which has form of a tube inside the crystal, wall of the tube is 2h, length is L, and radii is ≈(R1+R2)/2. We assume that the heat is generated homogeneously in the tube. Maximum temperature difference ΔT between surface and a centre (R=(R1+R2)/2) of the heat area in the crystal is $\Delta T=P_t x_0^2/2h\ 2s\ \chi_c$, here χ_c is thermal conductivity of the LiF crystal (χ_c=0.12 W/cm K [4]). This expression has been obtained at an assumption $x_0=(R_2-R_1)/2<<R_1$, R_2. Numerical estimation of ΔT gives us: ΔT=17 K at P_t=100 W, 2h=320 μm, s=66 cm^2, x_0=3 mm. This value of ΔT is not high and if the bulk metal is cooled to 0 °C, then highest temperature inside the crystal will be 27 °C if take into account the gap temperature step δT=10 °C. Thermal expansion of the LiF crystal in this case will be less then 50 μm. The considered above the crystal cooling scheme shows principal possibility to realise experimentally high output power LiF: F_2^- laser.

6. Estimation of pump YAG:Nd laser power and output LiF: F_2^- laser power needed to obtain 10- 50 W at 589 nm

Now let us relate heat power P_t and output power P of LiF:F_2^- laser. Our estimation is based upon results of low threshold experiments (see above 3). Initial transmission of the LiF: F_2^- crystal was 39%, so about half of pump power was passed through the crystal. If we denote absorbed pump power P_a, then equation for LiF: F_2^- laser output power P as function of P_a is $P=\eta_1 P_a-P_1$, where $\eta_1=\eta/0.5=0.057/0.5=0.114$. Internal resonator losses χ at wavelength of generation was $\chi=2\ln(1/T_2)=0.35$. As it is well known $\eta_1=\eta_0 \ln(1/R)/(\ln 1/R+\chi)$, here R is output mirror reflectivity (in our case R=95%), from this expression we find $\eta_1=0.128\ \eta_0$ and η_0=0.89. This value is close to limit due to Stocks shift. If we take output mirror reflectivity R=60%, and assume that area of mode inside the crystal is the same as it is in our experiment then $\eta=\eta_0 \ln(1/R)/(\ln 1/R+\chi)=0.52$, and P_1=4.6 W (because P_1 is proportional to ln(1/R)) and dependence of LiF: F_2^- laser output power as function of absorbed pump power become $P=0.52P_a-4.6$ (threshold 9 W of absorbed pump power). From this equation at P_a=200 W we have P=101 W or from absorbed 200 W pump power we have 100 W output power LiF:F_2^- laser radiation and almost 100 W is dissipated in the crystal as heat. This estimation proves value heat power P_t=100 W which we used above in calculation of temperature.

It was assumed above that pump beam is passing through LiF:F_2^- crystal in one direction only. Passed pump part is lost in this case. But if output mirror return pump beam back then the pumping efficiency will be about 2 times higher. In this case it is possible to consider that at pump power 200 W we obtain 100 W output at 1.18 μm.

To obtain radiation at 589 nm second harmonic generation in LBO crystal should be implemented. The peculiarities of LBO crystal as material for SHG have been discussed in [1].

Let us to have average output power of LiF:F_2^- laser 100 W. If we take into account that duty factor is 10 ("macropulse" duration 100 μc and repetition rate 1000 Hz) and "micropulse" duration is 0.3 ns with period 10 ns, then peak power of the laser radiation is 30 kW. If cross section area of the focused LiF:F_2^- laser beam in LBO SHG crystal is 10^{-4} cm^2, then we have the laser peak power density 3 10^8 W/cm^2 inside LBO crystal. It should be worse to remind that LBO crystal in our case has non-critical matching so it is possible to focus radiation into the crystal. This value of peak power density is high and it is possible to hope to reach 25%-50% SHG conversion efficiency which corresponds to 25 W - 50 W radiation at wavelength 0.589 μm.

7. LiF:F_2^- laser system with SHG with output power up to 50 W at 589 nm

In Fig. 11 there is scheme of the LiF:F_2^- laser system.

Pump YAG:Nd mode locked laser should to have the next characteristics:

Average output power	200 W
Pulse repetition rate	1kHz
Pulse duration	100 μs
Mode locking:	
Pulse duration	0.3 ns
Frequency	100 MHz
Transverse distribution	TEM_{00}

LiF:F_2^- laser resonator is presented in Fig. 1b but there should be added spectral selection element between lens (3) and output mirror (4). Parameters of the resonator are: radius of curvature of mirror (1) is 6.5 cm, radius of curvature of mirror (4) is 500 cm, lens (3) focal length is 20 cm, and l_1=6.1 cm, l_2=27 cm, d=250 cm. Output mirror reflectivity 60 %; LiF:F_2^- crystal transmission at wavelength 1.064 μm less then 50 %, length of the crystal 30 mm. The system of the crystal cooling is described above in section 5. The LiF:F_2^- laser resonator length and length of the pump YAG:Nd laser should be equal each other with accuracy several tenth of mm. There should to be some electronic system for automatically adjusting of lengths of these two resonators.

Transverse distribution matching optical system is situated between YAG:Nd laser and LiF:F_2^- laser. This system optical components parameters are depended on output parameters of pump laser (transverse distribution diameter and divergence), so at this stage of work it is too early to work out this system in detail.

At the output of the LiF:F_2^- laser there is LBO second harmonic generation system, which consists of two lens with equal focal lengths f, separated by distance $2f$, LBO crystal is situated in the middle between the lenses. The lens focal length depends on position of the SHG system with respect to LiF:F_2^- laser output mirror. If the system is close to this mirror then f=15 - 20 cm. This estimation is based on results of calculation of mode diameter inside the LiF:F_2^- laser resonator, which are presented in Fig. 2b. Output beam diameter at mirror 4 (Fig. 1b) is almost equal to that at the lens 3 (Fig. 1b). If a lens with the same focal length (f=20 cm) is implemented to focus output radiation into LBO crystal then cross section area at waist will be close to 10^{-4} cm^2 as it has been assumed above.

Conclusion

This report contains results of experimental and theoretical investigation of LiF:F_2^- laser.

1. Lowest known pump power threshold has been obtained for a long (100 μs) pump (at pump wavelength 1.064 μm).
2. Resonator configuration has been found, which is insensitive to focal length of a lens inside of active element.
3. Mode locked oscillation LiF:F_2^- laser has been tested.
4. Special system for cooling LiF:F_2^- crystal have been developed.
5. Paper design for LiF:F_2^- laser system with SHG with output power up to 50 W at 589 nm is presented.

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1. EOARD Contract F61708-97-W0127. Laser with Wavelength 0.589 μm ("Sodium Wavelength Laser"). Final Report, 12 May 1998.
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Principal Investigator N.N.Ilichev

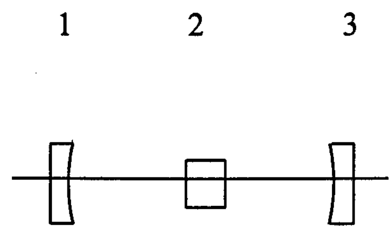


Fig.1a. "Short" resonator configuration; 1, 3 - resonator mirrors, 2 - LiF: F_2^- crystal which is placed in the middle of the resonator.

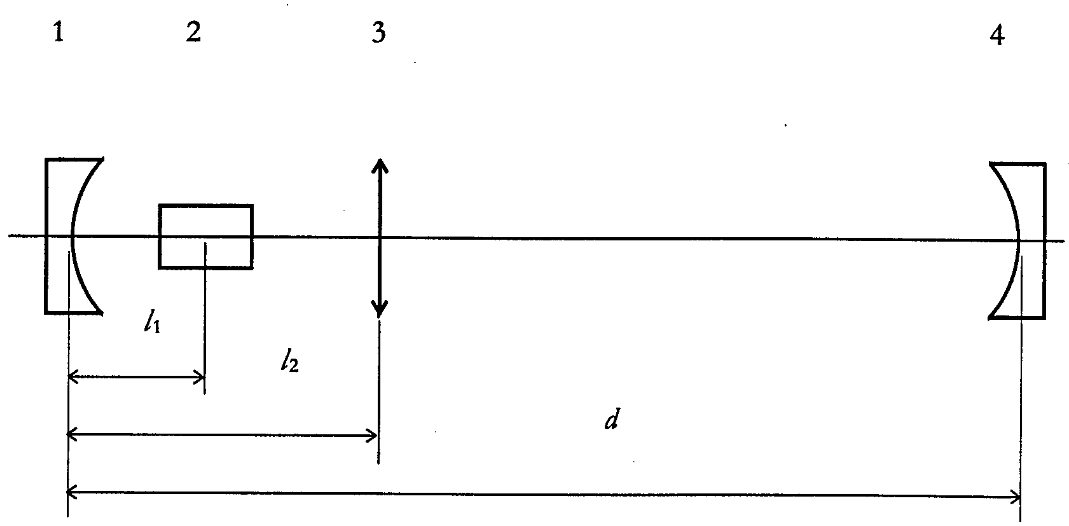


Fig.1b. Scheme of LiF: F_2^- - laser with "long" resonator: (1) - mirror, radius of curvature 6.5 cm, transmission at wavelength 1.064 μm - 70 %, reflectivity at wavelength 1.18 μm - 99 %; (2) - LiF: F_2^- crystal; (3) - lens with focal length +20 cm, AR coated at 1.18 μm; (4) - mirror, radius of curvature 500 cm, reflectivity at wavelength 1.18 μm - 90 %. Pump beam is passing through mirror (1).

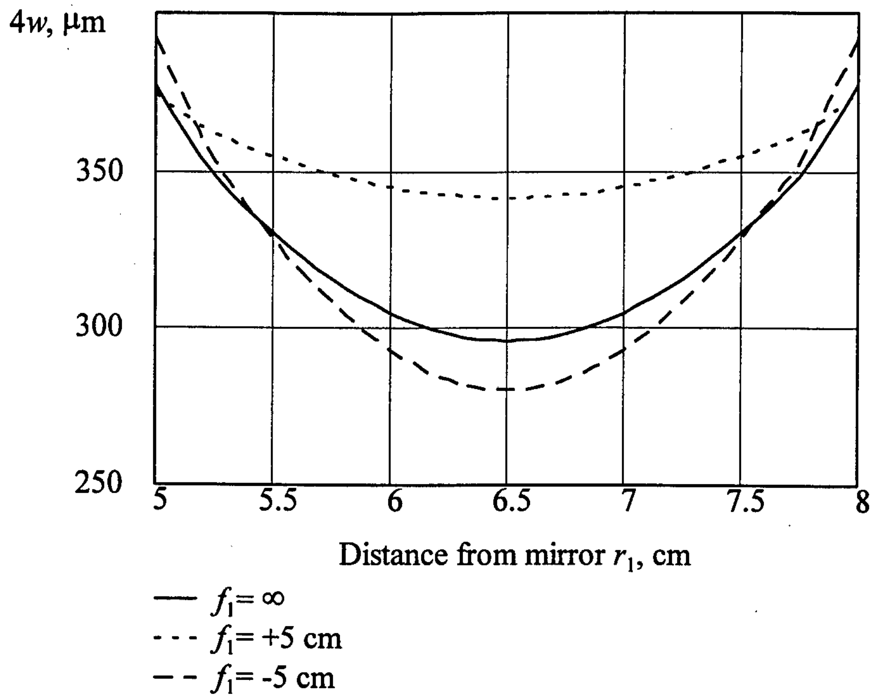


Fig. 2a. TEM_{00}-mode diameter ($4w$) inside LiF: F_2^- crystal for "short" resonator (see Fig. 1a); the crystal boundaries are 5.25 cm and 7.75 cm, l=2.5 cm; w is radius of Gaussian mode.

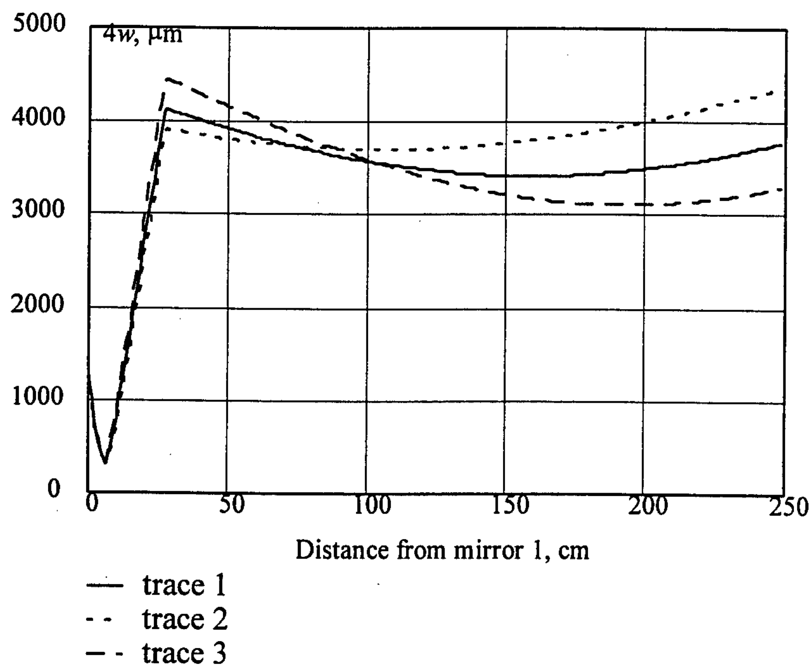


Fig. 2b. Dependence of TEM_{00} mode diameter at different places of LiF: F_2^- - laser resonator (see Fig. 1b). Three curves are correspondent to lens focal length in LiF: F_2^-: ∞- (trace 1), +5 cm (2), -5 cm (3).

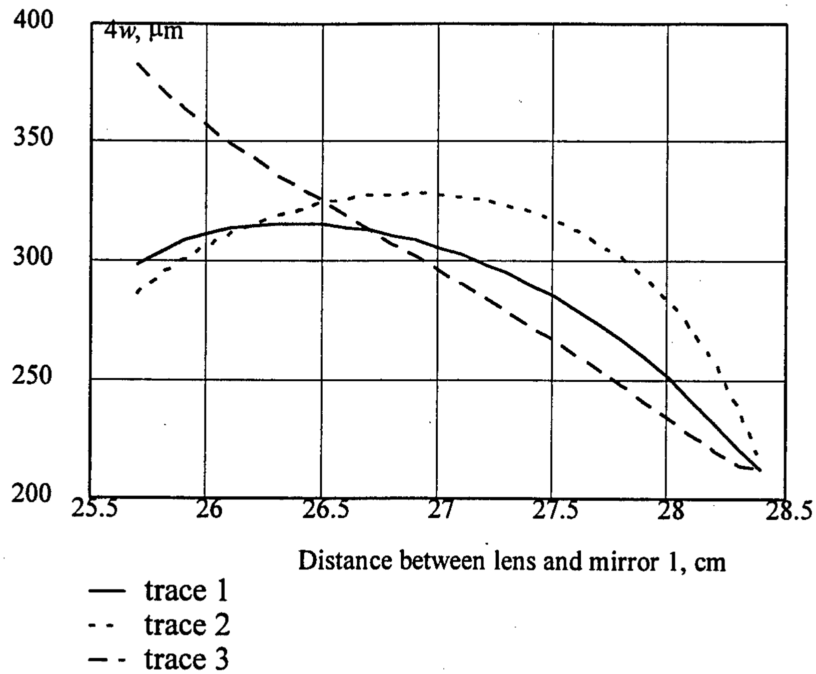


Fig. 3. Beam diameter in LiF:F_2^- active element as function of lens 3 position, d=250 cm; resonator configuration is presented in Fig. 1b. Three curves are correspondent to lens focal length in LiF:F_2^-: ∞- (trace 1), +5 cm (2), -5 cm (3).

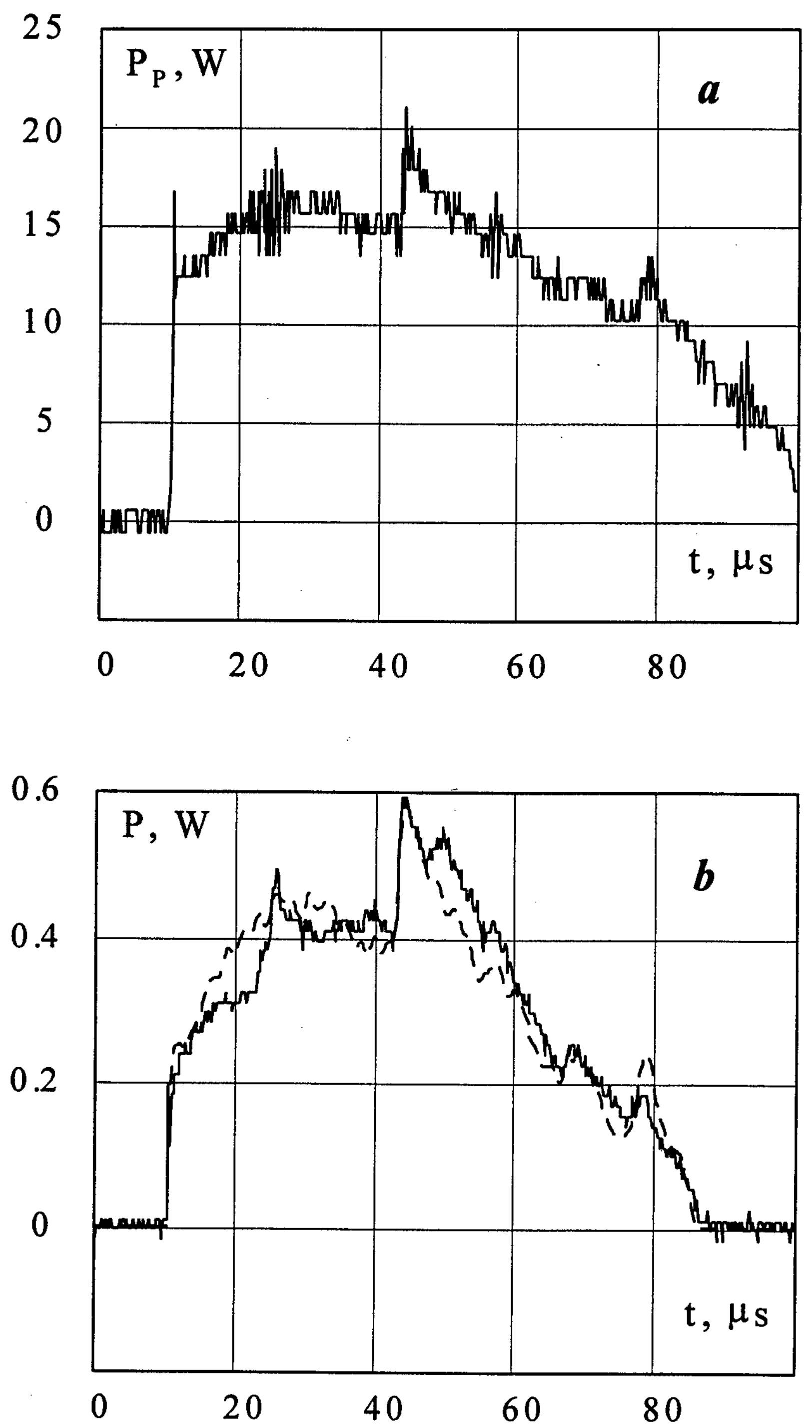


Fig. 4. Pump power at the input face of LiF:F_2^- (*a*) and output power of the LiF:F_2^- laser (*b*) (solid lines) as function of time. Dashed curve (*b*) is output power calculated on the base of pump one (*a*), with η=5.7% and P_1=0.46W (P_{th} = 8.2W).

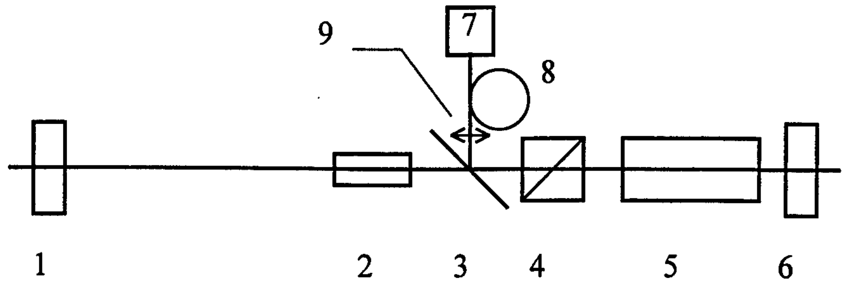


Fig. 5. Optical scheme of the neodymium laser with active mode-locking and negative feedback.

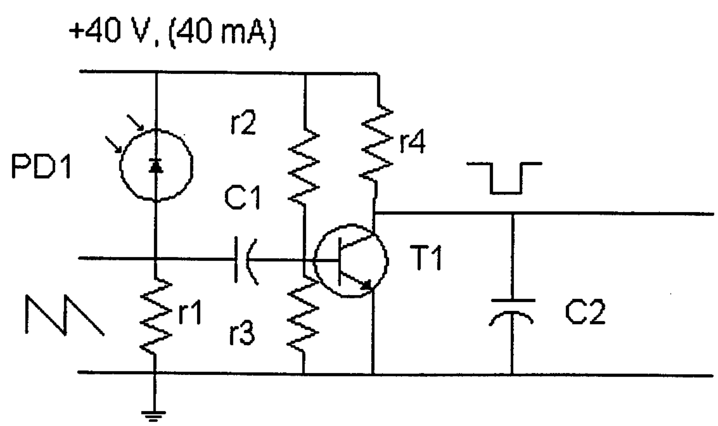
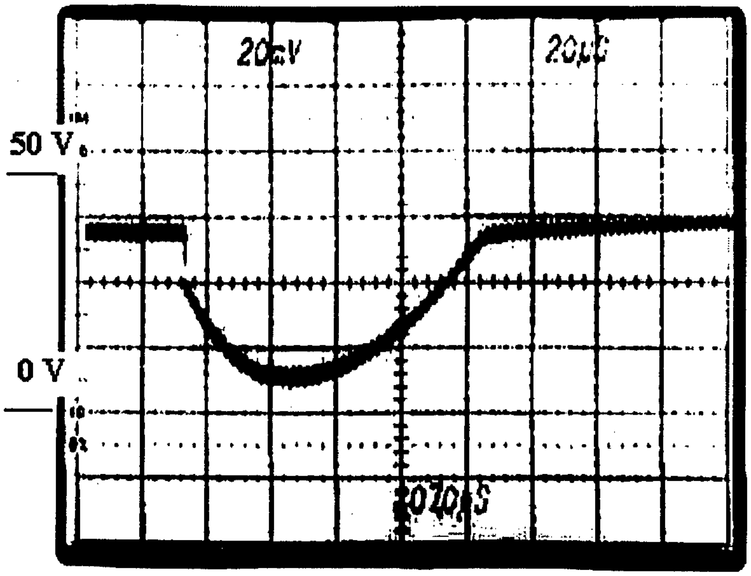
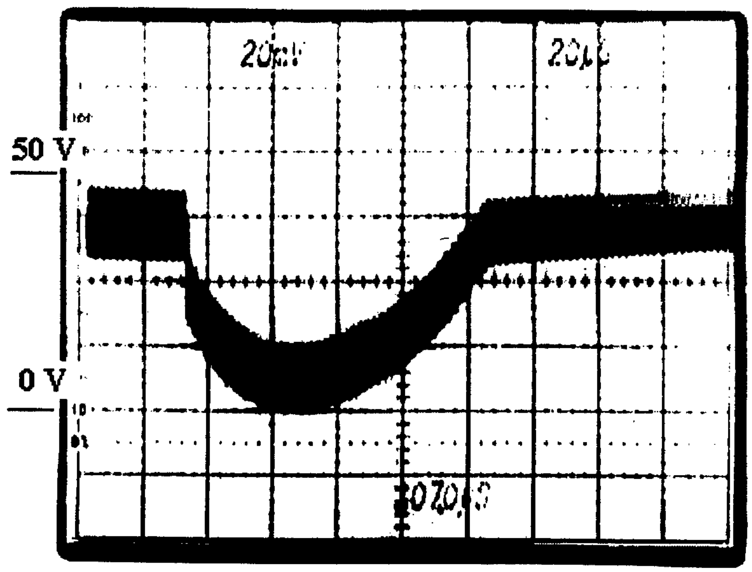


Fig. 6. Electric scheme for controlling voltage applied to EOM.



a



b

Fig. 7. Times dependence of voltage at EOM during generation: a - without HF-signal, b - with HF-signal (time scale - 20 μs/div).

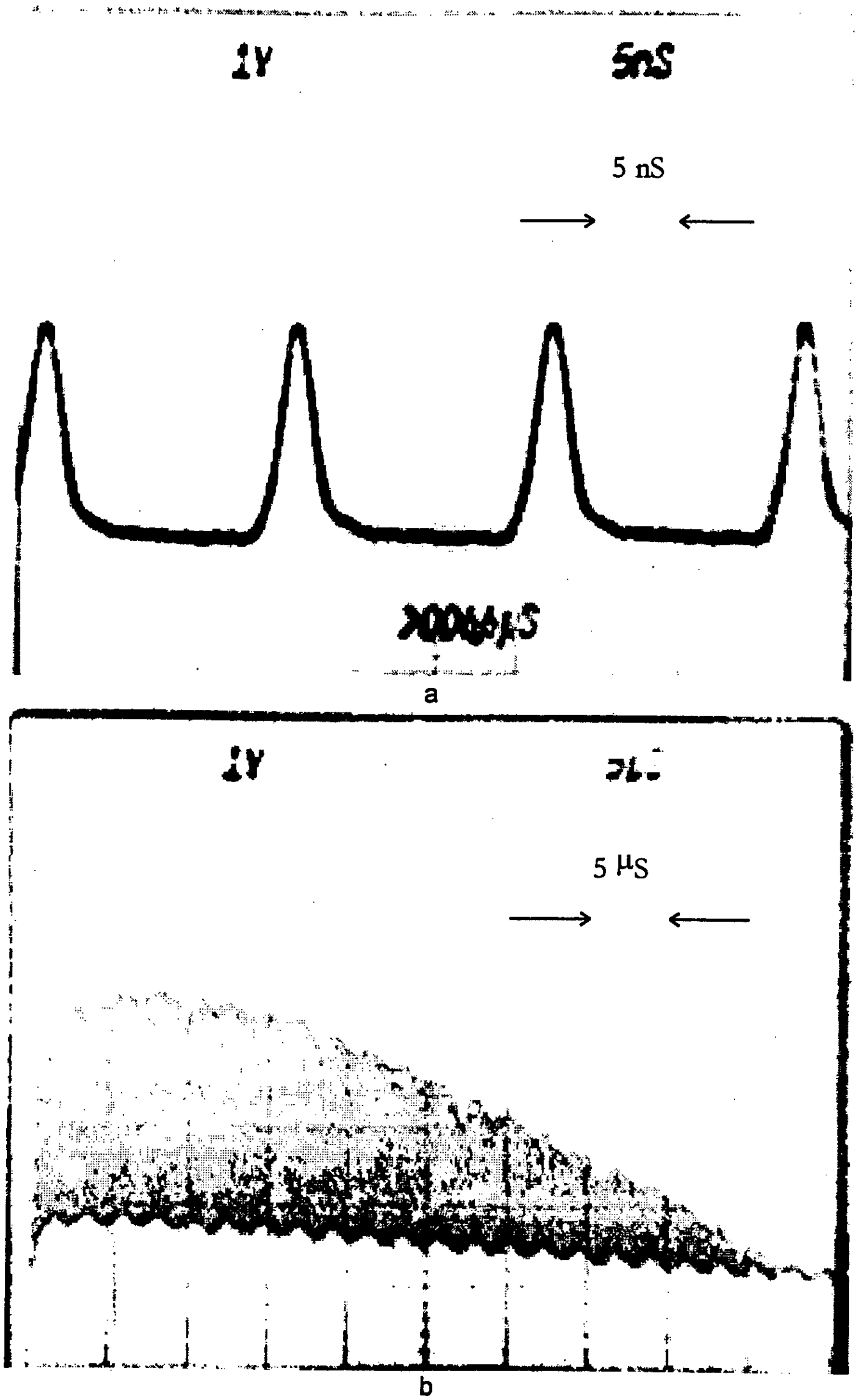


Fig. 9. Oscilloscope traces of LiF:F_2^- - laser radiation.

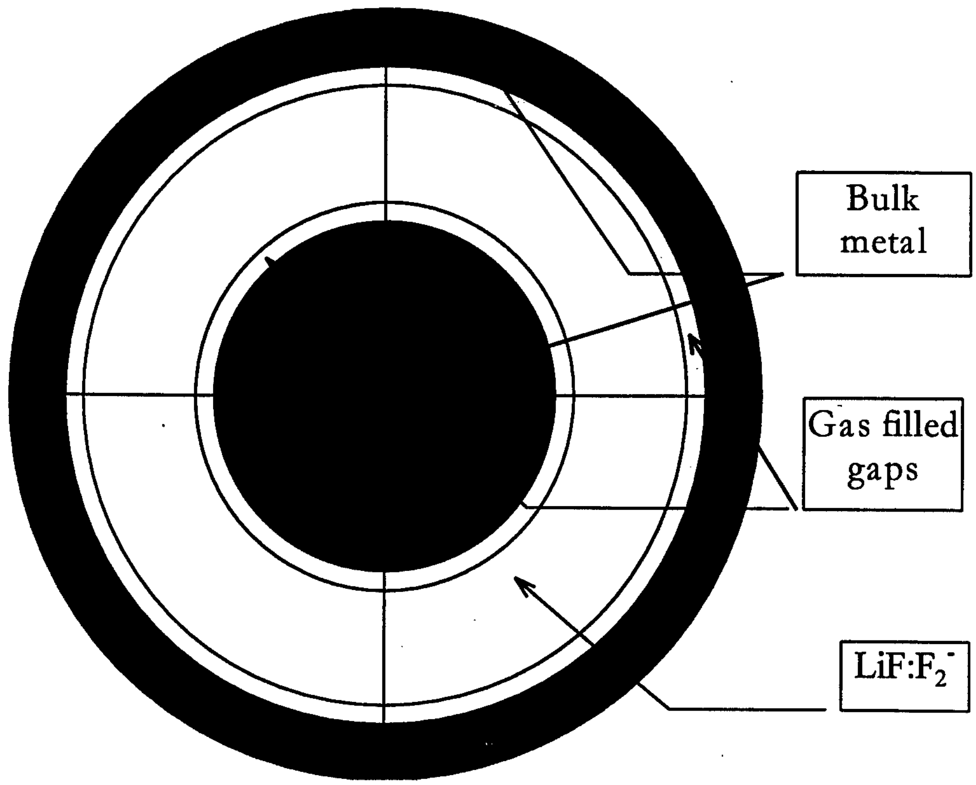


Fig. 10. Principal scheme of LiF:F_2^- crystal cooling.

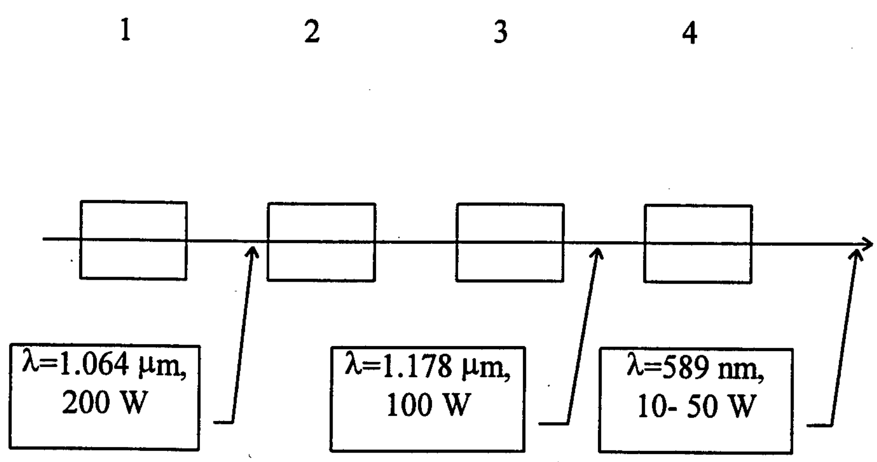


Fig. 11. Scheme of LiF:F_2^- laser system with SHG with output power up to 50 W at 589 nm. 1- YAG:Nd laser, 2 - transverse distribution pump radiation and LiF:F_2^- laser resonator matching system, 3 - LiF:F_2^- laser, 4 - LBO second harmonic generation system.