

DOI: 10.1070/QEL15991

High-power gas-discharge excimer ArF, KrCl, KrF and XeCl lasers utilising two-component gas mixtures without a buffer gas*

A.M. Razhev, E.S. Kargapol'tsev, D.S. Churkin

Abstract. **Results of an experimental study of the influence of a gas mixture (laser active medium) composition on an output energy and total efficiency of gas-discharge excimer lasers on ArF^* (193 nm), $KrCl^*$ (222 nm), KrF^* (248 nm) and $XeCl^*$ (308 nm) molecules operating without a buffer gas are presented. The optimal ratios of gas components (from the viewpoint of a maximum output energy) of an active medium are found, which provide an efficient operation of laser sources. It is experimentally confirmed that for gas-discharge excimer lasers on halogenides of inert gases the presence of a buffer gas in an active medium is not a necessary condition for efficient operation. For the first time, in two-component gas mixtures of repetitively pulsed gas-discharge excimer lasers on electron transitions of excimer molecules ArF^*, $KrCl^*$, KrF^* and $XeCl^*$, the pulsed energy of laser radiation obtained under pumping by a transverse volume electric discharge in a low-pressure gas mixture without a buffer gas reached up to 170 mJ and a high pulsed output power (of up to 24 MW) was obtained at a FWHM duration of the KrF-laser pulse of 7 ns. The maximal total efficiency obtained in the experiment with two-component gas mixtures of KrF and XeCl lasers was 0.8 %.**

Keywords: *two-component gas mixture, excimer laser, transverse volume electric discharge with UV pre-ionisation, gas mixture without a buffer gas, low total working pressure, generation energy, total efficiency.*

1. Introduction

All known excimer lasers on halogenides of inert gases with the pumping of an active gas mixture by a transverse volume electric discharge (hereinafter referred to as gas-discharge excimer lasers) utilise a high-pressure gas mixture (with the average total working pressure of about 2 atm) comprising at least three components. These are a buffer gas (He, Ne, Ar), a working inert gas (Ar, Kr, Xe) and halogen containing a gas that should include F, Cl and Br atoms. Buffer gases included in a gas mixture of typical commercial gas-discharge excimer lasers are the principal gas components, which may constitute about 90 % of the total working pressure in a gas mixture. For efficient operation (from the viewpoint of the energy and the operation time per single gas filling) of these lasers, a high-purity gas is used. For example, typical buffer gases in commercial models of laser systems are helium of grade 6.0, neon, or their combination. The cost of these gas components is sufficiently high. In the course of laser operation, the composition of the active laser medium (gas mixture) inevitably changes because of the arising impurities which result from the destruction of electrode materials and of the discharge chamber due to chemical reactions with halogen atoms produced in the discharge. The changes in the gas mixture composition inevitably reduce the generation energy in the course of laser operation and, consequently, the gas mixture needs regeneration.

Researchers try to find such exploitation conditions for laser sources, which provide a minimal expenditure and cost of gas components. In order to reduce the exploitation costs we study the possibility of operation of an excimer laser on two-component gas media comprising working and halogen-containing gases. Hence, it is important to study how the pump parameters and the composition of a low-pressure active medium affects the efficiency of gas-discharge excimer lasers operating on gas mixtures without a buffer gas.

It worth noting that in gas-discharge excimer lasers on mono-halogenides of inert gases, molecules are excited both in two-particle ('harpoon' reaction) and in tree-particle (ion–ion recombination) collisions. If the contribution of a harpoon reaction into the population inversion prevails, then the requirement of the high pressure of a gaseous active medium is not necessary. Excimer lasers on monohalogenides of inert gases operate at a lower working pressure than excimer lasers on dimers of inert gases. In the present work, we report the investigation results of only repetitively pulsed gas-discharge excimer lasers on mono-halogenides of inert gases pumped by a transverse volume electric discharge, operated at low pressure.

Among few works devoted to investigations of gas-discharge excimer lasers without a buffer gas one should mention papers [1–4]. Results on obtaining generation on excimer molecules $XeCl^*$, XeF^* and KrF^* in mixtures without a buffer gas under pumping by a transverse electric discharge were

*Reported at the Fifth Russian-Chinese Workshop and School for Young Scientists on Laser Physics and Photonics (RCWLP&P, Novosibirsk, August 26–30, 2015).

A.M. Razhev Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State Technical University, prosp. Karla Marksa 20, 630092 Novosibirsk, Russia; e-mail: razhev1950@mail.ru;
E.S. Kargapol'tsev Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: djohn797@mail.ru;
D.S. Churkin Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; e-mail: churkin@laser.nsk.ru

Received 7 December 2015; revision received 15 January 2016
Kvantovaya Elektronika **46** (3) 205–209 (2016)
Translated by N.A. Raspopov

first reported in [1]. The authors presented no measurement results concerning the energy and temporal characteristics of laser radiation. Seemingly, the radiation energy was low and insufficient for practical applications of the laser sources developed.

The authors of Refs [2, 3] also reported about obtaining a laser generation in exciting a two-component gas mixture by a longitudinal electric discharge. According to [2], the resulting generation on electron transitions of excimer molecules $XeCl^*$ was obtained at a minor content of the buffer gas He. At an active gas medium working pressure of about 0.06 atm, the radiation energy did not exceed 0.1 mJ. The absence of a buffer gas in the working mixture reduced the output energy almost twice.

In [3], the generation on electron transitions of excimer molecules KrF^* was obtained without a buffer gas. The output energy was at most 0.08 mJ at the active gas medium working pressure of about 0.4 atm. In [4], generation in two-component gas mixtures was obtained under the optical excitation of the active gas medium. The laser radiation was obtained on electron transitions of the excimer molecule $KrCl^*$. The generation energy was 0.001 mJ.

Analysis of experimental data in open literature makes one to conclude that radiation energy characteristics of excimer lasers on gas mixtures without a buffer gas are very low, which prevents such lasers from being employed in various applications. This is why we are aimed at developing and studying the possibility of creating high-power (megawatt) pulsed gas-discharge excimer lasers operating on two-component gas mixtures without an inert buffer gas, which would help realisation of efficient ablation of various materials and biological tissues and, consequently, employment of such lasers in medicine, microelectronics and other applications.

2. Equipment and measurement methods

The energy and amplitude-temporal characteristics of voltage and current pulses of an electric discharge and the parameters of radiation in the nanosecond range have been measured experimentally. The radiation energy was measured by a PE50-BB pyroelectric detector (Ophir Optronics Ltd), the profile of the radiation pulse was detected by a FEK-22 coaxial photoelectric cell. The amplitude-temporal characteristics were measured by a Tektronix TDS 220 oscilloscope, the voltage pulse was studied by using a P 6015A high-voltage probe (Tektronix). The parameters of current pulses were measured by a low-inductance ohmic shunt (with the resistance of 0.02 Ω). The accuracy of voltage and current amplitude measurements in all experiments was 5%.

3. Experimental setup

For realising a high efficiency of energy transfer from the storage circuit to the peaking circuit and depositing a high-intensity energy to the gas mixture it was necessary to construct a high-voltage exciting circuit with a minimal inductance. For optimising the operation regime it was necessary:

(i) to optimise the arrangement of high-voltage elements of the scheme for exciting a laser (the capacitor banks C_1, C_2, C_3, and a high-voltage switch); and

(ii) to reduce the inductance of the discharge circuit and introduce an additional inductance to a backward conductor for reaching the maximal efficiency of energy transfer from the storage circuit to the discharge circuit, which includes an active medium.

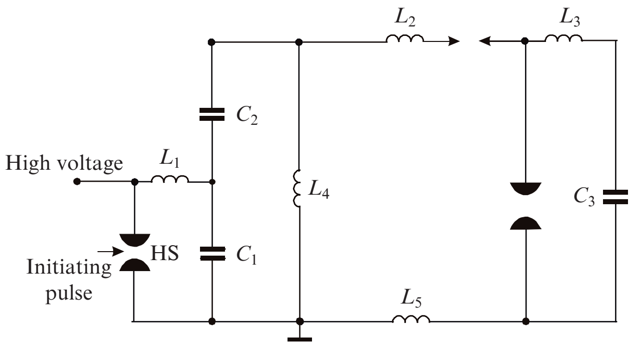

Figure 1. Electric circuit of laser pumping of the type *LC*-invertor: C_1 = 54 nF; C_2 = 103 nF; C_3 = 35 nF; HS is the high-voltage switch (TPI1-10k/20 thyratron); L_1 = 40 – 70 nH; L_2 = 20 nH; L_3 = 3.8 nH; L_4 = 2.5 μH; L_6 is the inductance of the bus bars.

The high-voltage electric circuit, which we have developed and described previously [5], is shown in Fig. 1.

L_2 is the inductance of the circuit of the *LC*-invertor and comprises the total inductance of spark gaps of UV pre-ionisation and capacitors C_1 and C_2. The inductance of the L_1C_1-circuit (L_1) is mainly determined by the inductance of a TPI1-10k/20 high-voltage switch; L_4 is the charging inductance. The inductance L_5 of bus bars affects the efficiency of energy transfer from storage capacitors to the peaking circuit and mainly determines the efficiency of the circuit operation (see [5]). A choice of the inductance L_5 allows one to increase the voltage across the capacitor bank C_3 and, thus, to increase the discharge current, which results in a higher energy deposition. In addition, an increase in the inductance L_5 is accompanied by a delay of the instant of discharge gap breakdown, i.e., results in a longer delay t between the start of UV pre-ionisation (a breakdown of the discharge gaps) and the pulse of the discharge current. A later breakdown of the discharge gap is preferable from the viewpoint of increasing the homogeneity of pre-ionisation of the gas medium. Hence, as the range of optimal t values is approached (200 – 300 ns), the output energy and efficiency of the laser increase.

Capacities C_1 (54 nF) and C_2 (103 nF) are the banks of TDK UHV-6A capacitors (2.7 nF, 30 kV) comprising 20 and 38 pieces, respectively. Thus, the total charge capacitance was 157 nF. After the high-voltage switch (TPI1-10k/20 thyratron) triggers and the polarity of voltage across C_1 changes, the capacitors C_1 and C_2 recharge to C_3 and their shock capacitance becomes equal to 35 nF. The bank C_3 comprised TDK UHV-8A capacitors (1.3 nF, 40 kV), which were arranged from two sides of the discharge chamber directly on the latter (along it) for attaining a minimal inductance of the discharge circuit. The bank C_3 (31 nF) was charged from C_1 and C_2 through 78 chokes 1 μH each, connected to the spark gaps of UV pre-ionisation for their synchronous operation. The total inductance of the chokes connected in parallel was 12.8 nH, and the charge inductance L_4 was 2.5 2 μH.

Laser electrodes were made of nickel. In experiments, the electrodes with the working surface radii of 50 cm (anode) and 100 cm (cathode) were used. A distance between the electrodes was 2.1 cm, a length of the active medium was 59 cm; thus, at the discharge width of 0.8 cm the active volume was 100 cm^3. An automatic UV pre-ionisation was performed by two rows of spark gaps with a separation of 2 mm. From each side of the high-voltage electrode at a distance of 10 mm from its edge, there were 39 spark gaps for enhancing the homogeneity of UV pre-ionisation of the discharge gap and reducing the inductance of the high-voltage exciting scheme. The chamber was encapsulated by plane-parallel plates made of CaF_2 (VUV), one of them being an outcoupling mirror of the cavity. External dielectric mirrors with the maximal reflection coefficients corresponding to the wavelength of laser operation were used as the second mirror. The cavity length was 120 cm. A gas mixture was transversely pumped through the discharge gap at a rate of 12 m s^{-1}, which provided laser operation at a pulse repetition rate of 50 Hz and higher.

4. Experimental results

Below we present experimental results of investigations of energy and temporal radiation parameters for excimer gas-discharge ArF, KrCl, KrF and XeCl lasers versus the pump parameters and the composition of the gas mixture at a low working pressure, with no buffer gas.

4.1. Excimer ArF laser (193 nm)

An experimental dependence of the generation energy and total efficiency (Fig. 2) on the discharge voltage U_{ch} in the range of 15–26 kV was obtained for a two-component (Ar and F_2) excimer ArF laser without a buffer gas in the active medium.

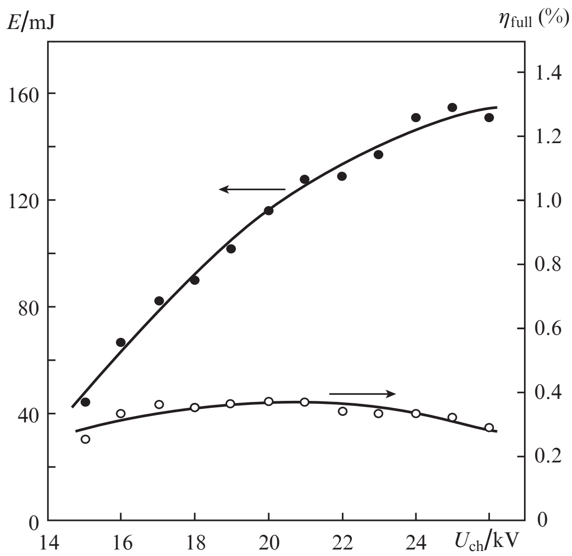

Figure 2. Output laser energy E and total efficiency η_{full} of a two-component ArF laser vs. the charge voltage U_{ch} at a linear increase in the total pressure of the gas mixture from 0.7 to 1.2 atm.

From this dependence one can see that with increasing charge voltage and, correspondingly, pressure of the working mixture (from 0.7 to 1.2 atm) the generation energy rises from 40 to 160 mJ. Hence, in pumping the gas mixture with no buffer gas at a pressure of 1.2 atm by a transverse electric discharge, for the first time the obtained energy of an ArF laser was 160 mJ at the total efficiency of about 0.3%. Negligible variation of the efficiency with an increase in pumping testifies that the specific power of pumping the two-component ArF laser was close to optimal. At the FWHM duration of a radiation pulse 8 ± 1 ns, the pulsed power reached 19.5 MW. In the present work, the total laser efficiency implies the ratio of the generation energy to the energy stored in the storage capacitor ($C_1 + C_2$) of the high-voltage electric excitation circuit (hereinafter simply efficiency).

4.2. Excimer KrCl laser (222 nm)

An experimental dependence of the generation energy and total efficiency (Fig. 3) on the discharge voltage U_{ch} in the range of 20–26 kV was obtained for a two-component (Kr and BCl_3) excimer KrCl laser with no buffer gas in the active medium.

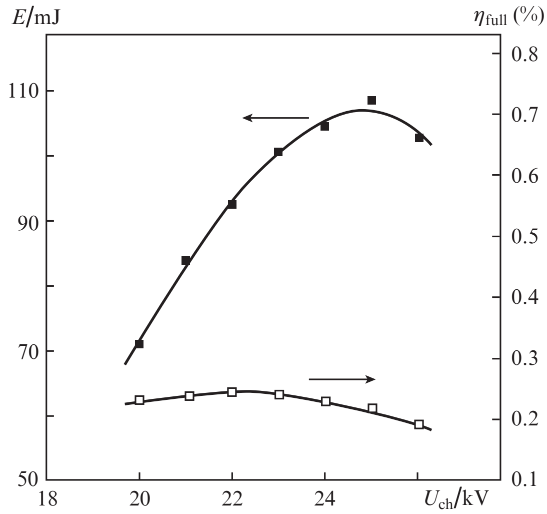

Figure 3. Same as in Fig. 2, for a two-component KrCl laser under increasing total pressure of the gas mixture from 1.1 to 1.3 atm.

From this dependence one can see that with increasing charge voltage and, correspondingly, pressure of the working mixture (from 1.1 to 1.3 atm) the generation energy rises from 70 to 110 mJ. However, starting with 25 kV, the radiation energy of the two-component KrCl laser falls due to deterioration of the discharge homogeneity and nonoptimal conditions of depositing energy stored in the peaking capacitor into the active medium. Hence, in pumping the gas mixture without a buffer gas at a pressure of 1.2 atm by a transverse volume electric discharge, for the first time the obtained energy of a KrCl laser reached 110 mJ at the efficiency of about 0.25%. At the FWHM duration of a radiation pulse 8 ± 1 ns, the pulsed power reached 14 MW.

Also, an experimental dependence of the generation energy on the charge voltage U_{ch} in a range of 10–26 kV was obtained for a two-component (Kr and HCl) excimer KrCl laser with gaseous HCl used as a halogen-carrying agent. With increasing charge voltage and, correspondingly, working pressure of the gas mixture (from 0.9 to 1.1 atm), the generation energy rises up to 90 mJ. At the FWHM duration of the radiation pulse 7 ± 1 ns, the pulsed power reached ~13 MW.

4.3. Excimer KrF laser (248 nm)

An experimental dependence of the generation energy and the total efficiency (Fig. 4) on the discharge voltage U_{ch} in the

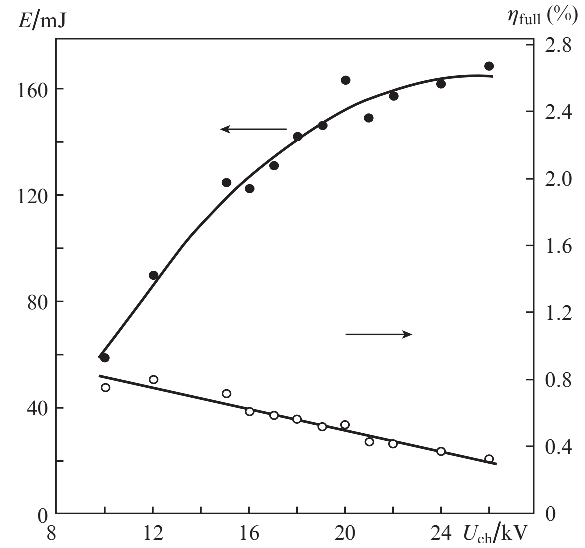

Figure 4. Same as in Fig. 2, for a two-component KrF-laser under increasing total pressure of the gas mixture from 0.4 to 1.1 atm.

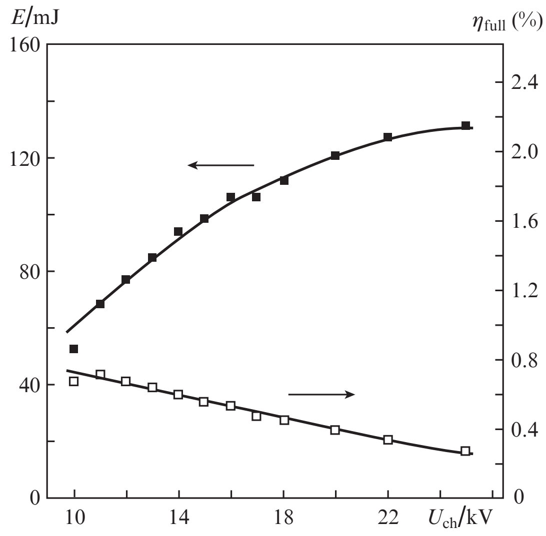

Figure 5. Same as in Fig. 2, for a two-component XeCl-laser under increasing total pressure of the gas mixture from 0.45 to 0.65 atm.

range of 10–26 kV was obtained for a two-component (Kr and F_2) excimer KrF laser with no buffer gas in the active medium.

From this dependence one can see that with increasing charge voltage and, correspondingly, pressure of the working mixture (from 0.4 to 1.1 atm) the generation energy rises from 60 to 170 mJ. Hence, in pumping the two-component gas mixture of the KrF laser without a buffer gas at a pressure of 1.1 atm by a transverse volume electric discharge, for the first time the obtained energy of an ArF laser reached 170 mJ at the efficiency of about 0.3%. At the FWHM duration of a radiation pulse 7 ± 1 ns, the pulsed power reached 24 MW. The maximal efficiency obtained at the minimal charge voltage of 10 kV and the working pressure of 0.4 atm was 0.8%. In this case, the generation energy was 60 mJ per pulse.

Also, an experimental dependence of the generation energy on the charge voltage U_{ch} in the range of 15–26 kV was obtained for a two-component (Kr and NF_3) excimer KrF laser with gaseous NF_3 used as a halogen-carrying agent. With increasing charge voltage and, correspondingly, working pressure of the gas mixture (from 0.6 to 0.8 atm), the generation energy rises to 115 mJ. At the FWHM duration of a radiation pulse 14 ± 1 ns, the pulsed power reached ~8 MW.

An influence of pumping on the value of the active volume of a two-component KrF laser was investigated. It was shown that the discharge width determines the value of the active volume of the laser and varies with the discharge voltage and composition of a gas mixture. It was found that with increasing charge voltage from 10 to 26 kV in an excimer KrF laser with the two-component gas mixture, the optimal pressure increases from 0.4 atm to 1.1 atm; the discharge width rises from 0.6 to 0.8 cm and, consequently, the active volume changes from 75 to 100 cm^3.

4.4. Excimer XeCl laser (308 nm)

An experimental dependence of the generation energy and total efficiency (Fig. 5) on the discharge voltage U_{ch} in the range of 10–26 kV was obtained for the two-component (Xe and BCl_3) excimer XeCl laser with no buffer gas in the active medium.

From this dependence one can see that with increasing charge voltage and, correspondingly, pressure of the working mixture (from 0.45 to 0.65 atm) the generation energy rises from 50 to 130 mJ. Hence, in pumping the gas mixture without a buffer gas at a pressure of 0.65 atm by a transverse volume electric discharge, for the first time the obtained energy of a XeCl laser reached 130 mJ at the efficiency of about 0.3%. Also, an experimental dependence of the generation energy on the charge voltage U_{ch} was obtained for a two-component (Xe and HCl/CCl_4) excimer XeCl laser with gaseous HCl and CCl_4 used as halogen-carrying agents. With increasing charge voltage and, correspondingly, working pressure of the gas mixture, the maximal generation energies were 70 and 50 mJ, respectively. The homogeneity of the radiation energy distribution over the cross section of the output laser beam was estimated by using a thermo-sensitive paper. A footprint of a laser beam on its surface exhibits high homogeneity of the laser energy distribution over the cross section – both in height and width of the laser beam.

5. Conclusions

For the first time, in repetitively pulsed gas-discharge excimer lasers operating on electron transitions of excimer molecules ArF^*, $KrCl^*$, KrF^* and $XeCl^*$ under pumping of a low-pressure gas mixture without a buffer gas by a volume electric discharge, the pulse energy of laser generation reached 170 mJ at a high (up to 24 MW) pulsed power of laser radiation with a uniform energy distribution over the cross section of the output beam. The maximal efficiency obtained in an experiment with two-component gas mixtures of KrF and XeCl lasers reached 0.8%.

Energy and temporal characteristics of the repetitively pulsed lasers elaborated on the basis of the study provide their efficient application. For example, for the first time, a XeCl laser utilising both a three-component active gas medium and two-component gas mixtures (without a buffer gas) was used to create and efficiently employ an UV ophthalmologic system for medical treatment of patients with open-angle glaucoma [6, 7]. A gas mixture was transversely pumped through a laser emitter by a centrifugal fan, which provided laser operation in a repetitively pulsed regime with a pulse repetition rate of up to 50 Hz. Operation at the pulse repetition rate above 50 Hz was not studied because of the lack of such an operation regime in a medical UV ophthalmologic system.

References

1. Zubrilin N.G., Milanich A.I., Chernomorets N.P., Yurchuk S.V. *Kvantovaya Elektron.*, **12** (3), 643 (1985) [*Sov. J. Quantum Electron.*, **15** (3), 423 (1985)].
2. Fedorov A.I. *Opt. Atmos. Okeana*, **7** (1), 96 (1994) [*Atmos. Ocean. Opt.*, **7**, 53 (1994)].
3. De la Rosa J., Eichler H.-J. *Opt. Commun.*, **64** (3), 285 (1987).
4. Basov N.G., Zuev V.S., Kanaev A.V., Mikheev L.D. *Kvantovaya Elektron.*, **12** (11), 2197 (1985) [*Sov. J. Quantum Electron.*, **15**, 1449 (1985)].
5. Razhev A.M., Shchedrin A.I., Kalyuzhnaya A.G., Ryabtsev A.V., Zhupikov A.A. *Kvantovaya Elektron.*, **34** (10), 901 (2004) [*Quantum Electron.*, **34**, 901 (2004)].
6. Chernykh V., Ermakova O., Iskakov I., Razhev A., Churkin D., Kargapoltsev E. *Proc. XXXII Cong. Europ. Soc. Cataract and Refractive Surgeons* (London, UK, 2014).
7. Chernykh V.V., Ermakova O.V., Iskakov I.A., Razhev A.M., Churkin D.S., Kargapol'tsev E.S. *Tezisy Vseross. Nauchno-prakticheskoi konf. 'Novye tekhnologii v oftal'mologii-2015'* (Abs. All-Russian Conf. 'Advanced Technologies in Ophthalmology-2015') (Kazan: Slovo 2015).