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ORIGINAL ARTICLE

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Preliminary results of development of a single-mode Q-switched Nd: YAG ring laser at 213 nm and its application for the microsurgical dissection of retinal tissue ex vivo

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Abstract The Nd: YAG laser family offers wide possibilities for surgery applications in medicine. The radiation at 213 nm provides similar tissue effects as compared to 193 nm excimer lasers, but offers considerable practical advantages in the operating room. As such, it is of considerable interest to create single-mode Q-switched fifth harmonic Nd: YAG pulsed lasers with a high coefficient of efficiency and low divergence. Parameters of the ring three-mirror anisotropic cavity TEM_{00}-Nd: YAG laser were calculated on the basis of the analysis of Gaussian beam behavior in the three-mirror ring cavity, with one convex spherical mirror and one intracavity positive lens. On the hand of numerical calculations a prototype of a single-mode Q-switched Nd: YAG-213 nm laser with an output energy of 4 mJ and a beam divergence of 1 mrad has been developed. At a pulse repetition rate of 50 Hz, it has a generation efficiency in the Q-switched mode of 0,6%. A hollow core wave guide is used in combination with a short length of a special fused silica optical fiber to guide the laser beam. Full-depth dissection of rabbit retina ex vivo was achieved at the intensities of 0.18–0.05 J/cm^2 and a repetition rate of 50 Hz, with a linear cutting rate of 6 mm/s. Although the retina was completely cut, heat necrosis of the choroid did not occur. We are currently in the process of testing the dissection of retinal tissue during retinotomy, and the formation of holes in the trabecular meshwork in glaucoma surgery.

Keywords Pulse-periodical operation · DUV 213nm-laser system · TEM_{00} Q-switched Nd: YAG laser · Three-mirror anisotropic cavity · intraocular surgery · Retinotomy

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Introduction

The use of lasers in surgery and medicine began rapidly after the development of the first working laser system, however, the development of practical, effective, and safe surgical lasers has been lengthy, with many obstacles and delays. Today in many areas of medicine Nd: YAG lasers have already become versatile tools for tissue removal and coagulation [1–11].

In ophthalmology, the dissection of retinal tissue during retinotomy, and the formation of holes in the trabecular meshwork in glaucoma management, is performed with Nd: YAG lasers at 532 and 1064 nm [4–10]. Corneal ablation for the correction of refractive errors is an expanding field in ophthalmology. In addition to the common excimer lasers, the use of solid state fifth harmonic Nd: YAG laser systems at 213 has become popular because of the ability to control the microsurgical effects by manipulation of energy distribution and regulation of deep ultra violet (DUV) power [11–17]. They are compact, low in cost, easier to maintain, and utilize no toxic gases [17–20], thus developing efficient pulsed single-mode Q-switched Nd: YAG lasers with low divergence is very worthwhile.

In this work, we present numerical and experimental results of research on the generation characteristics of single-mode Nd: YAG laser with a ring three-mirror anisotropic cavity, as well as give some preliminary results on cutting of the rabbit retina ex vivo with a microsurgical laser scalpel based on a commercially available solid state DUV laser system at 213 nm.

Analysis of Gaussian beam behavior in the three-mirror ring cavity

To begin the analysis of Gaussian beam behavior in the three-mirror ring cavity with one convex spherical mirror and one intracavity positive lens, we will consider at first general features of three-mirror ring cavities with planar geometry, the scheme of which is given on Fig. 1. It is known that with an odd quantity of mirrors the beam phase after tracing the cavity is rotated by 180 degrees. To return the beam into the initial phase, an even number of mirror reflections is needed, which can be accomplished through an additional trace of the cavity (see Fig. 1).

This means that light beams of the final aperture will be regenerated after two traces of the three-mirror ring cavity, which in its turn promotes that radiation of similar beams and more uniformly fills a prolonged active medium. This makes the single-mode generation easier and allows simultaneous high efficiency and high spatial coherence [20, 21].

Let us consider the features of Gaussian beams spreading clockwise in the ring three-mirror cavity (see Fig. 2a). In this cavity, a thin positive lens with focusing distance f_a is placed at a distance l_1 from a convex spherical mirror M_1 with a radius of curvature r.

On the other hand, the distance from the lens to the spherical mirror M_1 is $L_2 = L_r - L_1$. The distance from the lens to the flat output mirror P_2 is $L_{P2} = (L_r - 2L_1)/2$. By retracing its path through the ring cavity, the beam passes through the positive lens f_a.

A general idea about Gaussian beam behavior in the ring cavity can be obtained by examining the features

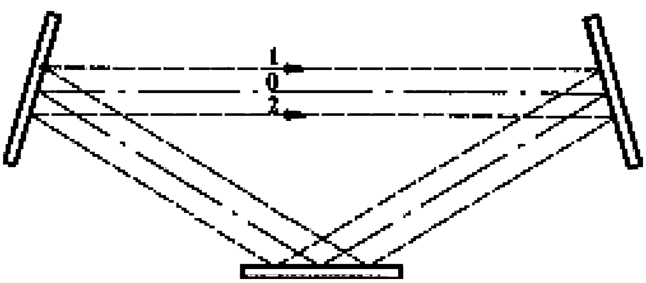

Fig. 1 Three-mirrors ring cavity with flat axis contour. Note: With an odd quantity of mirrors the beam position after tracing the cavity is changed to opposite. To return the beam into the initial position “0” an additional tracing of the cavity is needed

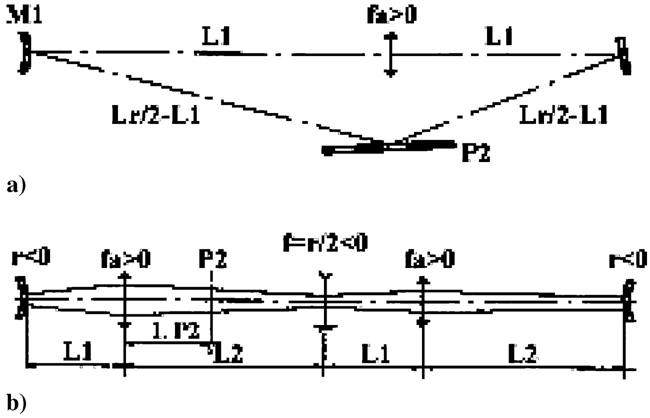

Fig. 2 Features of Gauss beam behaviour in the ring cavity. **a** Gauss beams spreading clockwise in the ring three-mirror cavity with a thin positive lens and a spherical mirror M_1. **b** Equivalent linear cavity with the length $L = 2L_r$ consisting of convex spherical mirrors $(r < 0)$ as ring mirrors, two positive $(f_a > 0)$ and one negative $(f = r/2 < 0)$ lenses

of a linear cavity of length $L = 2L_r$ where convex spherical mirrors with a curvature radius $r < 0$ are used as ring mirrors, and two thin positive lenses with a focusing distance $f_a > 0$ and one thin negative lens with a focusing distance $f = r/2 < 0$ are placed between them(see Fig. 2b).

In the linear cavity, the plane P_2 is placed at a distance $L_1 + L_{P2}$ from the convex spherical mirror on the left side. Using the method of *ABCD* matrixes, it is possible to calculate the stability of the linear cavity, the width of the beam ρ, and the radius of curvature R of the wave front.

Conditions for the stability of the linear cavity are as follows: $0 < G_1 G_2 < 1$, where $G_1 = A_1 - B_1/r$, $G_2 = D_1 - B_1/r$. Coefficients A_1, B_1, C_1 and D_1 are the coefficients of the matrix of one trace from the left mirror to the right one:

$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} = M(L_2) * M(f_a) * M(L_1) * M(f) * M(L_2) * M(f_a) * M(L_1)$$

Beam parameters in the plane P_2 situated at a distance $L_1 + L_{P2}$ from the left mirror are calculated by the formulae:

$R = 2B/D - A$ – curvature radius of the wave front,

$\rho = \sqrt{\lambda |B| / \pi} \sqrt{1 - (D + A/2)^2}$ - beam radius.

A,B,C, and D are the coefficients of a matrix for the full trace of the cavity, which can be written as:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = M(L_{P2}) \bullet M(f_a) \bullet M(L_1) \bullet M(r) \bullet M(L_1) \bullet M(f_a) \bullet M(L_2) \bullet M(f) \bullet M(L_1) \bullet M(f_a) \bullet M(L_2) \bullet M(r) \bullet M(L_2) \bullet M(f_a) \bullet M(L_1) \bullet M(f) \bullet M(L_1 - L_{P2}).$$

With the help of the ABCD matrix method, beam parameters in any sections of the cavity can be calculated. Given R and ρ, the divergence for Gaussian beams is $\sqrt{(\theta_\lambda^2 + \theta_g^2)}$, where $\theta_\lambda = \lambda/\rho\sqrt{\pi}$, being the diffraction component of divergence, and $\theta_g = \rho\sqrt{\pi}|R|$, being the geometrical component of divergence.

Numerical calculation

On the basis of the above given formulas there were calculated parameters of the Gaussian beam in the plane P_2. For numerical calculations the following values were used:

– Curvature radius of the convex spherical mirror r = −5000 mm and r = −8000 mm,
– Focal length of the positive lens $f_a = +2500$ mm,
– The distance between spherical elements $L_1 = 185$ mm, $L_2 = 611$ mm.

The results of the numerical calculations are given in the table 1. It can be seen from the table that increasing the radius of curvature of the convex mirror increases the stability of the cavity, decreases the beam radius, and increases the divergence.

Calculations show that with the curvature radius of the spherical mirror r = −5000 mm, the beam radius inside the cavity changes in the following way:

– at the left mirror $\rho = 1382$ mm
– at the first positive lens after the left mirror $\rho = 1434$ mm
– at the negative lens $\rho = 1265$ mm
– at the second positive lens $\rho = 1311$ mm
– at the right mirror $\rho = 1158$ mm

Table 1 Numerical calculations of the three-mirrors ring cavity

Parameters	r = −5000 mm	r = −8000 mm
$G_1^\bullet G_2$	0.901	0.533
R [mm]	$-4.86^\bullet 10^3$	$-4.87^\bullet 10^3$
ρ[mm]	1.32	0.869
θ_d[mrad]	0.45	0.69
θ_g[mrad]	0.48	0.31
θ[mrad]	0.66	0.76

Taking the above into account, the characteristics of a Gaussian beam spreading clockwise in a ring cavity seem to change as they would in a linear cavity. Since the Gaussian beam fills a large volume of the active medium, it is evident that the single-mode generation will be efficient, which is confirmed experimentally (generation efficiency in the Q-switched mode is equal to ~0.6%). Additionally, the Gaussian beam is convergent at the plane P_2.

Laser system configuration

Based on numerical calculations, a prototype of a single-mode Nd: YAG laser with a three-mirror ring anisotropic cavity has been developed. The scheme of the single-mode Q-switched Nd: YAG laser ring cavity is displayed in Fig. 3.

As an active element, a YAG: Nd^{3+} crystal with a diameter of 4 mm and length of $l_a = 60$ mm with features of a heat lens and a positive focusing distance of $f_A \approx 2.5$ m was used. The ring cavity with a length of $L_c \approx 0.85$ m was created by two flat mirrors M_2 and P_2 and one convex spherical mirror M_1 with the radius of curvature $r_1 = 5$ m. As an output mirror, we used a thin film polarizer with an incidence angle of 56°, the transmission coefficient of which for a wave traveling clockwise was regulated by turning a half-wave phase plate $\lambda/2$. A half-wave electro-optical shutter containing a DKDP crystal and thin film polarizer P_1 was used as a Q switch.

A Diaphragm D with diameter of 2.5 mm was used for unidirectional operation and angle selection. In this cavity, the waves traveling clockwise around the ring fill a large volume of the active medium. Radiation losses for waves traveling clockwise are comprised of polarization losses from transmission at the output mirror P_2 and aperture losses at the diaphragm. Cavity modes with counter-clockwise direction are small and fill a smaller central zone of the active medium. Radiation losses for waves traveling counter-clockwise are stipulated by polarization losses on reflection from polarizer P_1.

It was ascertained that in the free running mode, the ratio of traveling wave energies was $E^+/E^- \approx 3$, where E^+ is the energy of radiation pulses spreading clockwise, and E- is the energy of radiation pulses spreading

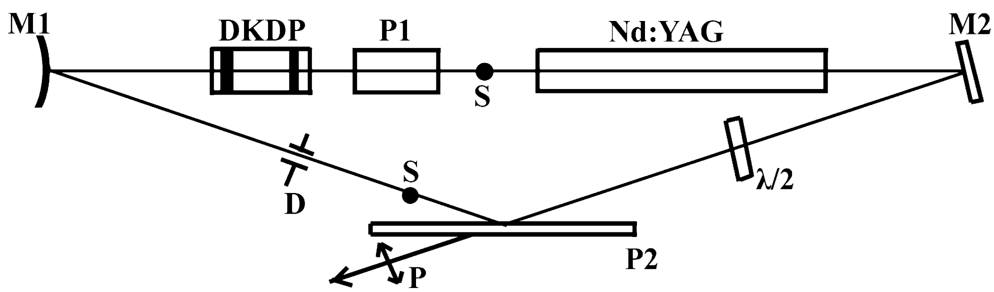

Fig. 3 The scheme of the single-mode Q-switched Nd: YAG laser with ring cavity

counter-clockwise. In the Q-switched mode, the proportion of traveling waves energies was $E^+/E^- > 30$, which indicated a real unidirectional operation mode. The laser system works well with a repetition rate at 50 Hz. The maximum energy that can be supplied to the flashlamp is 15 J. With pump $P_p = 750$ W the Nd: YAG laser generated pulses up to 100 mJ, 13 ns in duration, with a divergence of 0.6 mrad. The beam diameter at the output mirror P_2 was 3 mm.

It should be stated that the generation beam behind the output mirror P_2 was slightly convergent. After exchanging the spherical mirror M_1 with radius of curvature $r_1 = 5$ m for another spherical mirror with radius of curvature $r_1 = 8$ m, the divergence increased to 0,8 mrad, and the generation pulse energy was 100 mJ, thus yielding nearly identical results.

Commercial Nd: YAG laser system at 213 nm

Based on the above scheme of the single-mode Q-switched Nd: YAG ring cavity laser, the commercially available LQ129C has been developed [22]. It contains all the advantages of complex high-performance laser configurations and is designed on the "oscillator only" scheme. The unit, a photo of which is shown in Fig. 4, includes the units LG103 [23] for third and LG105 [24] for fifth harmonic generation.

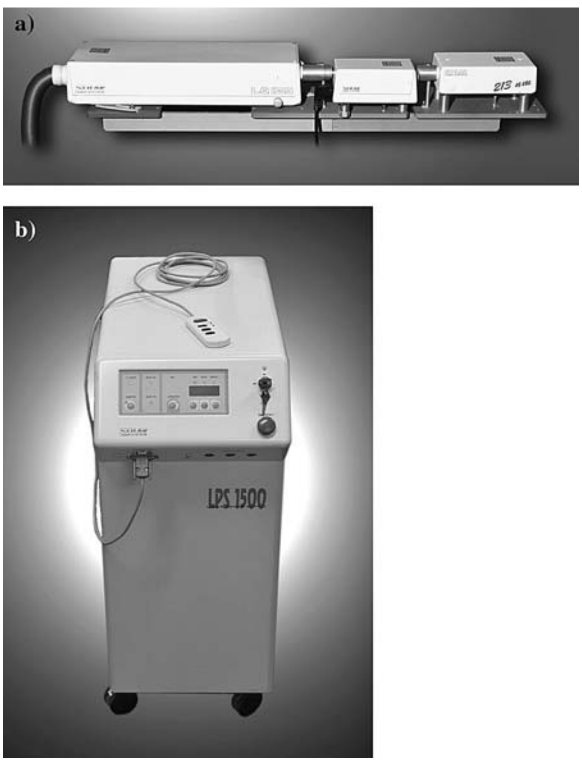

Fig. 4 Single mod Q-switched 213 nm-Nd: YAG-laser system LQ129C with an anisotropic ring-cavity from SOLAR LS Inc., Belarus. **a** Laser head. **b** Power supply

A power supply unit and a self-contained water-to-air cooling system are integrated into a common housing providing all logic, electrical, and cooling components necessary for laser operation. Computer control using the optional RS232 interface allows integration into laboratory or process automation systems. Compact size and a closed loop cooling system, which requires no external water, permits placement of the power supply under an optical bench or another convenient small area.

The output parameters of the single mode Q-switched Nd: YAG-laser system LQ129C with an anisotropic ring-cavity are presented in Table 2.

Medical application of the DUV Nd: YAG-laser scalpel

A DUV Nd: YAG-laser scalpel based on a hollow core waveguide with an inner diameter between 0.5 mm and 1.0 mm was built [25]. The inner wall of the capillary is coated with a thin film of aluminum, which possesses a high reflection coefficient (up to 80%) for the UV light at 213 nm and carries the light to the tip of the endoscopic probe. This hollow core waveguide is flexible with a minimum bending radius of 0.3 m.

The tip of the endoscopic probe can be joined to a 20-gauge disposable needle (Fig. 5). For a first impression of the performance of the laser scalpel we cut an enucleated rabbit retina. Beginning from about 0.05 J/cm^2 it was possible to incise rabbit retinas completely without any damage of the underlying retinal pigment epithelium (Fig. 6). At the expected cutting speed for the retina of approximately 0.6 mm/s the width of the cut is about 150 μm (Fig. 7).

Discussion

It was shown experimentally that in the Q-switched mode a unidirectional operation with the proportion of traveling waves $E^+/E^- > 30$ is observed in the ring Nd:

Table 2 Output parameters of a Q-switched Nd:YAG laser LQ129C with a three-mirrors ring cavity

Pulse repetition rate, Hz	50
Output energy, mJ	
at 1064 nm,	150
at 532 nm	80
at 355 nm	35
at 266 nm	20
at 213 nm	4
Pulsewidth, nsec	12
Beam diameter, mm	≅5
Divergence, mrad	≥1
Power consumption, (single phase, 220 V ± 10%, 50/60 Hz) VA	> 1000
Laser head, mm	490(L)×180(W)×90(H)
Power supply, mm	770(H)×340(W)×670(D)

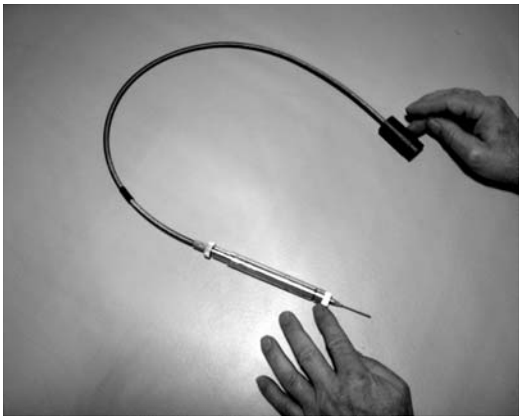

Fig. 5 The appearance of a hollow core waveguide for DUV laser radiation. The tip of a handpiece can joint 20-gauge disposable needle, capable of the insertion through 1-mm sclerotomy site

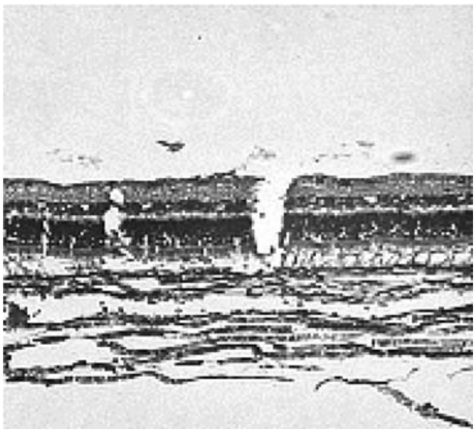

Fig. 6 Histologic section of rabbit retina incised with 213 nm laser. The repetition rate was 50 Hz; the output energy 0.05 mJ/cm^2. The full-depth sharp transection of the retina was obtained. Underlying retinal pigment epithelium looked intact. Hematoxylin and eosin; original magnification ×100

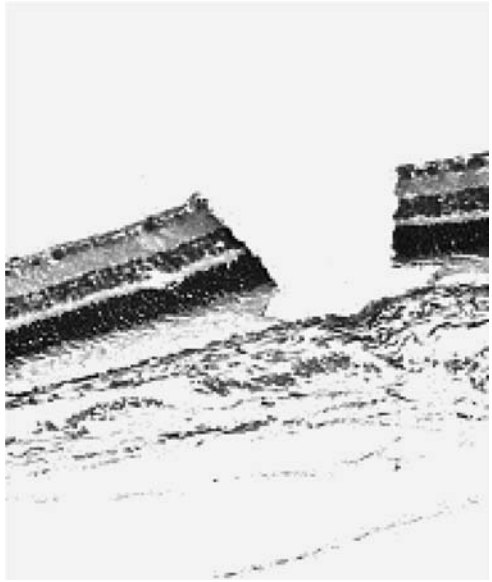

Fig. 7 Histologic section of rabbit retina incised with 213 nm laser. The repetition rate was 50 Hz; the output energy 0.18 mJ/cm^2. The full-depth sharp transection of the retina was obtained. Underlying retinal pigment epithelium looked intact. Hematoxylin and eosin; original magnification ×100

YAG laser. To explain the observed mode of the unidirectional operation, we will consider a process of amplification of waves traveling clockwise and counter-clockwise during the trip through the cavity from the moment the shutter is opened.

In the ring laser, polarization dictates the radiation output, creating a wave moving clockwise (due to transmission of polarizer P_2), and a wave moving counter-clockwise (due to reflection from polarizer P_1). The coefficient of output of radiation from the cavity is regulated by the half-wave plate, useable losses for traveling waves being $k^+ = k^- = \sin^2(2\phi)$, where ϕ is the turn angle of the phase plate relative to the direction of the maximal transmission of polarizer P_2.

For the wave moving clockwise, the polarization condition in the active medium remains unchanged, i.e. in the plane perpendicular to the plane of the cavity (s-component). Having passed the phase plate, this wave has 2 components: a weak s-component, which after reflection from polarizer P_2 returns to the active medium, and a strong p-component, which is transmitted by polarizer P_2.

The wave traveling counter-clockwise (s-component), having passed the phase plate, also has 2 components: a weak s-component and a strong p-component. Because of the concurrence in the active medium, the p-component is more amplified than s-component. This implies that the effective amplification of waves with s-polarization moving clockwise will be higher than for waves moving counter-clockwise. At high amplification of the active medium for the Q-switched mode, it is possible to operate unidirectionally, which is confirmed experimentally.

We also demonstrated a flexible beam guiding system for high power DUV Nd: YAG-laser at 213 nm, where the intensity at the distal end is sufficient to ablate various types of medical tissues. Full-depth dissection of rabbit retina ex vivo was achieved at the intensities of 0.18–0.05 J/cm^2 and a repetition rate of 50 Hz, with a linear cutting rate of 6 mm/s without any heat damage of the choroids.

In summary this paper concludes that DUV Nd: YAG laser scalpel operated well within the safety limits of Nd: YAG lasers at 532 and 1064 nm [5, 10] and may greatly facilitate tractionless dissection of tissue in liquid media.

Conclusion

Our empirical evaluations of a three-mirror ring cavity Nd: YAG laser with show that cavities with one convex spherical mirror and polarization, it is possible to:

- generate one TEM_{00} mode filling a large volume of the active medium;
- operate unidirectionally at the expense of difference in amplifier coefficients for waves spreading in opposite directions;
- create pulsed single-mode Q-switched fifth harmonic DUV Nd: YAG lasers with a high coefficient of efficiency and a low angle of divergence.

Based on the three-mirror ring cavity DUV Nd: YAG laser, we have designed a new laser scalpel for vitreoretinal surgery, using a new flexible, durable, mobile wave guide connected to a hand-held endoprobe with a 20-gauge needle. We suggest that this new DUV Nd: YAG laser scalpel may to be applied to intraocular surgery for vitreoretinal diseases.

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References

1. Monga A, Kumar D, Jain SK (2002) Laser palliation of esophageal carcinoma. J Assoc Phys Ind 50:1017–1021
2. Venuta F, Rendina EA, De Giacomo T, Mercadante E, Francioni F, Pugliese F, Moretti M, Coloni GF (2002) Nd:YAG laser resection of lung cancer invading the airway as a bridge to surgery and palliative treatment. Ann Thorac Surg 74:995–998
3. Ogura M, Sato S, Ishihara M, Kawauchi S, Arai T, Matsui T, Kurita A, Kikuchi M, Ashida H, Obara M (2002) Myocardium tissue ablation with high-peak-power nanosecond 1,064-and 532-nm pulsed lasers: influence of laser-induced plasma.Lasers Surg Med 31:136–141
4. Liu DT, Lai JS, Lam DS (2002) Descemet membrane detachment after sequential argon-neodymium: YAG laser peripheral iridotomy. Am J Ophthalmol 134:621–622
5. Ivanov AN (2002) Laser instrumental surgery in prevention and treatment of retinal detachment. Vestn Oftalmol 118:13–16
6. Abreu MM, Sierra RA, Netland PA (1997) Diode laser-pumped, frequency-doubled neodymium: YAG laser peripheral iridotomy. Ophthalmic Surg Lasers 28:305–310
7. Bandello F, Brancato R, Lattanzio R, Trabucchi G, Azzolini C, Malegori A (1996) Double-frequency Nd: YAG laser vs. argon-green laser in the treatment of proliferative diabetic retinopathy: randomized study with long-term follow-up. Lasers Surg Med 19:173–176
8. Fankhauser F, Kwasniewska S (2002) Laser vitreolysis. A review. Ophthalmologica 216:73–84
9. Fine HI, Packer M, Hoffman RS (2002) New phacoemulsification technologies. Update/review. J Cataract Refract Surg 28:1054–1060
10. Delaney YM, Oyinloye A, Benjamin L (2002) Nd: YAG vitreolysis and pars plana vitrectomy: surgical treatment for vitreous floaters. Eye 16:21–26
11. Dair G, Ashman RA, Reinholz F, Eikelboom RH, van Saarloos PP (2001) Absorption of 193 and 213 nm laser wavelengths in saline and balanced salt solution. Arch Ophthalmol 119:533–537
12. Dair GT, Pelouch WS, van Saarloos PP, Lloyd DJ, Paz Linares SM, Reinholz F (1999) Investigation of corneal ablation efficiency using ultraviolet 213 nm solid state laser pulses. IOVS 40:2752–2756
13. Dair GT, Pelouch WS, van Saarloos PP, Lloyd DJ, Paz Linares SM, Reinholz F (1999) Investigation of corneal ablation efficiency using ultraviolet 213 nm solid state laser pulses. IOVS 40:2752–2756
14. Reinholz FR, Paz Linares SM, van Saarloos PP, Humphris S (1999) Wound healing after PRK using a 213 nm solid state laser. IOVS 40:585
15. Pelouch WS, van Saarloos PP, Dair G, Lloyd DJ and Paz S (1998) Results of corneal ablation by ultraviolet 213-NM laser pulses. IOVS 39:310
16. Shen JH, Joos KM, Manns F, Ren Q, Fankhauser F 2nd, Denham D, Soderberg PG, Parej JM (1997) Ablation rate of PMMA and human cornea with a frequency-quintupled Nd: YAG laser (213 nm). Lasers Surg Med 21:179–185
17. Stamm U, Zschocke W, Schröder T, Deutsch N, Basting D (1997) High efficiency UV-convection of a 1 kHz diode-pumped Nd: YAG laser system. OSA TOPS 10:7–9
18. Lin JT (1997) Critical review on refractive surgical lasers. Optical Engineering 34:668–675
19. Schastak S, Kondratjuk N, Molotkov D, Schagov A and Wiedemann P (1998) New possibilities of generating tunable radiation in the deep UV-region from 190 to 199 nm in solid state laser systems. Lasermedizin 14:36 – 40
20. Schastak S, Gulevich E, Kondratjuk N, Schagov A, Wiedemann P (2000) Wide beam oscillator-amplifier device for industrial or medical laser. DE19855801
21. Ananiev Y A (1990) Optical resonators and laser beams. Nauka Publishers, Moscow
22. Pulsed Nd: YAG Laser LQ 129C (2002) User's Manual, SOLAR LS/Minsk/Republic of Belarus
23. Third/fourth harmonic generator LG 103 for Nd: YAG lasers. (2002) User's manual, SOLAR LS/Minsk/Republic of Belarus
24. Fofth harmonic generator LG 105 for Nd: YAG Lasers. (2002) User's manual, SOLAR LS/Minsk/Republic of Belarus
25. Hillrichs G, Dietz H, Rütting M, Schastak S, Wiedemann P, Matsuura Y, Miyagi M, Klein KF (2002) Flexible beam guiding in a microsurgical UV laser scalpel. Proc SPIE 4616:199–206