# Two-Line High-Power Single Active Element Nd:YAG Quantum Electronics Generator with Coaxial Architecture-Optimization

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*Abstract* – **On the base of our patented principle, we have proposed and realized a high energy output, two-wavelength Nd:YAG optical quantum-electronics generator (OQEG -i.e. laser) that oscillates in a single active element with a single pumped arrangement at two chosen laser lines (pair from 1.06; 1.32, 1.34, 1,36 and 1.44 μm). The generations are produced in two coaxially disposed and optically separated parts of the laser rod, each generated in its own resonator. The basic advantage of our coaxial architecture is that in conveniently chosen condition, the focusing effect by the external Nd:YAG crystal part increases the pump energy density (~2½ times) into the internal, axial part and thus facilitates strongly the generation in this part at the weaker lasing lines. Thus, we can balance the energy output for both lines – the weak being generated in the internal part and the stronger - in the external one. In this report we develop the approach to improve the coaxial-geometry dual-line lasers by applying a convenient technique for elimination of the parasitic lasing in the periphery of the laser rod. This consideration primary applies for flash-lamp pumped Nd:YAG OQEG, however it is of general character and can be applied for different type of such coaxial-geometry dual-line lasers–e.g.such with side-diode-pumping.**

*Keywords* – **two-lines Nd:YAG laser (Optical quantum generator), coaxial geometry, active rod focussing effect, parasitic oscillation**

## I. INTRODUCTION, THE AIM OF THE WORK

Laser light at two wavelengths (when the spectral distance between the wavelengths is high at two lines) frequently is used in the systems for distant monitoring of the composition of gaseous pollutants and aerosols in the atmosphere (LIDAR), in differential absorption spectroscopy, in lifetime measurements of energetic levels in spectroscopy, in frequency mixing in nonlinear optics, in holography, in metrology [1-3]. The usefulness of the two-wavelength laser light for the noted applications increases essentially when the two lines are emitted as high energy and power laser beams, with independent tuning and also in adjustable temporal sequence - simultaneous or with controlled nano- or microsecond delay. Such light can be obtained in most simple and chipper manner, using a single laser with a single active element that generates the two wavelengths in convenient laser architecture [4-9]. The high energy output can be obtained using a flash-lamp or diode side pumping [10-12]. The functionary of the dual-line lasers can be essentially better if the laser light is generated in separated volumes in the laser rod so that the wavelength competition effect can be avoided that worsens strongly the emissions characteristics [11, 13].

Earlier, we have patented a flashlamp-pumped condensed matter laser, containing a single, cylindrical active element composed of two coaxially disposed separated active media that operate at two different colors [4]. Such types of solutions for lasers were also reported latter, independently of us, in Refs. [5] and [6]. The general advantage of our coaxial architecture laser solution is the naturally present focussing effect that increases essentially the pump density in the near axial part of the laser crystal rod. As we have shown here, this focussing effect can increase the pump power density in the inner axial medium ~2½ times for a Nd:YAG rod, in general accordance whith that for the ruby and Nd:Glass [10,14]). Thus, in the coaxial dual line laser architecture proposed by us, the internal part can operate effectively at weaker lasing lines and the internal part in the low pump energy density at stronger ones, permitting to equalize the output energies in both emissions without losses of pump energy. The two lights are emitted in coaxial beams that fills all laser rod volume.

We have realized such a dual-line laser (chosen pairs between 1.06, 1.32, 1.34, 1.36, 1.44 μm) at the example of a single Nd:YAG active laser rod with flash lamp pumping. The last solution is shortly described in this report and, also, as an essential point, we present here a new technique to improve the dual line, coaxial geometry OQEG architectures. This is done by the conveniently chosen Nd:YAG laser rod parameters and a convenient treatment of the rod to avoid the parasitic laser generation in the periphery.

## II. THE DUAL-LINE OQEG USING THE PROPOSED COAXIAL ARCHITECTURE

*Setup of the coaxial geometry tunable dual-line laser*

The optical scheme of the proposed two-line Nd:YAG coaxial architecture laser is presented in Figure 1. For the advantageous realization of the proposed laser we use low-$Nd^{3+}$-doping (in our work ~0.5 at %) Nd:YAG crystal. Such doping, instead of typical ~1 %, is also commonly used [e.g. in 15] and assures sufficient efficiency of the generation in combination with high quality of the output beam. The cylindrical YAG rod (diameter Ø= 0.7 cm and length l= 8 cm) was with AR coated for 1.06 μm faces equipped with slight frosting of the envelope wall. Our

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study shows that a laser active element with given parameters assures a notable focusing effect in the axial region resulting in an increase of ~2½ times for the pump power density in the near axial rod part (Figure 2). In the experimental arrangement, the laser rod was in a close position with a pump flash-lamp in a commercial pump-chamber with UV-absorbing elliptic cylinder-pump light concentrator (doped quartz by silvered walls; axes 23 x 29 mm, length 78 mm) and with holes for the laser rod and the lamp of ∅ 9.5 mm and 11.5 mm. The lamp (IFP 1200 type, 700 Torr of Xe, ∅ 0.95 cm, Russia) and the crystal were surrounded with cooled flowing destilled water at temperature 18 ± 0.3$^{o}$ C. The electrical supply was standard, homemade, providing electric energy of 100 J in ~400 μs FWHM lamp pulse duration (at 1 Hz repetition rate.)

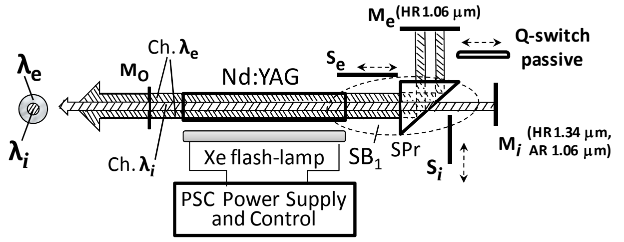


Fig. 1. Optical scheme of the developed tunable two-wavelength coaxial-geometry Nd:YAG lasers using as separator a prism SPr with a hole or a Brewster cylinder and a selective-mirror resonator.

We have realized such dual-wavelength, coaxial-geometry high efficiency laser for generation at 1.34 μm in the internal resonator and at 1.06 in the external resonator and vice-versa (the experiment described below). If the user dispses of appropriate sets of mirrors he can chosen also the other pairs of lines, using the same principle described below. The light generation at two wavelengths was achieved in two, coaxially arranged and optically separated parts of the Nd:YAG laser rod each equiped with its own resonator (length of 40 cm). In the external, hollow-cylinder part of the active medium and its resonator, the light at the first wavelength $\lambda_e$ (channel for generation at $\lambda_e$) is generated and the second – in the coaxial internal part and its resonator - light at the wavelength $\lambda_i$. (channel for generation at $\lambda_i$). The resonator of the first cahnnel consistd of the output mirror $M_0$, common for both resonators (reflectivity of 80% for 1.32 - 1.36 μm, 75% for 1.44 μm and $R_3$=35 % for 1.06 μm) and the end mirror $M_e$ (for generation of the line $\lambda_e$ = 1.06 μm with reflectivity of 98 %; for the line 1.34 μm the miroor $M_e$ was with specific reflection : for 1.3 μm of 95 % and AR for 1.06 μm). The resonator of the internal part consists of Mo and this one of $M_e$ (for generation at 1.34 um with reflection for1.34 μm of 95 % and AR coated for 1.06 μm; when a line 1.06 μm was generated in this resonator with reflectivity of 99 %).The optical separation of the two parts and of their resonators (hatched differently in Figure 1) is realized using a rectangular prism SPr with a hole (in our experiment with 4 mm diameter) through the cathetus and the hipotenuse. The hole axis is inclined at an angle of ~5$^{o}$ with respect to the cathetus plane to avoid non-desired Frenel reflection feadback. The optical axis of the internal rod part and its resonator point through the center of this hole. A very thin metal tube with ~0.12 mm thick walls and 30 mm legth was introduced in the hole (the length of the latter 6 mm). The external part is coupled with its resonator by reflection of the SPr outside the hole. The described SPr assures very good separation of the two channels. The separation of the channels also was obtained using a Brewster angle cut at one end of the small diameter, glass cylinder as it is shown in the inset in Figure 1(a). This arrangement, is very effective and simple, however, such a realization is advantageous if the laser rod is fabricated with this appendix specially for dual-line laser operation. For tuning of an arbitrary pair of lines, the mirrors $M_1$ and $M_2$ can be changed by the prism selective blocks that is not considered in this report.

*Experimental investigations: single- and coaxial dual-color laser operation*

Firstly, we will present some experimental results for single line generation, that relate with the study of two-wavelength lasing. For single line generation of the entire $Nd^{3+}$:YAG rod (without separation, RPr removed, electrical pumping of 100J) the output energy at 1.06 μm was 570 mJ. The lasing threshold was ~13J. The free lasing spatial intensitiy distribution was the superposition of the $TEM_{00}$ and $TEM_{01}$* modes [4]. The output at 1.34 μm line for the full rod was 320 mJ (through output coupler with transmission T=20%) and 70 mJ through the end mirror (T= 5%).

An important investigation, concerning the dual-line operation and the focusing effect into the rod, was the study of the radial pump density distribution in the pumped laser rod. The study employed generation for the 1.06 μm line. This study was accomplished by the measurement of the laser output energy $E_{dr}$, generated in the described above non-selective flat-flat mirror resonator for 1.06 μm generation described above, when a diaphragm with a hole diameter d=2mm was introduced in the resonator at one of the ends of the laser rod and was translated radially along the crystal diameter. The measured output energy $E_{dr}$ and the knowledge of the volume of the lasing part (cylinder with Ø 0.2 cm and length of 8 cm axis with axis parallel to the rod axis), enable to obtain the pump energy density for this cylinder. The latter was obtained by comparing the measured output energy with the diaphragm and the energy, obtained by solving the differential equation system that describes the Nd:YAG laser operation with the laser medium parameters corresponding to our experiment. We have calculated the laser output for a variety of pump energy densities to obtain the one, that gives the measured $E_{dr}$. The pump energy density $\rho_{pump}$ obtained in this manner as a function of the radial diaphragm center position x = r is given in Figure 2. Note that, due to the translation of the diaphragm inside the resonator, we obtain exactly the generation in the part of the rod selected by the diaphragm, thus avoiding the influence of the mode structure distribution completely being the case if the entire rod generates (the measurement is done outside the resonator). The ~2½ time increase of the pump energy in the near axial part is due to the focalizing effect [10,14]). Thus the choosen parameters – low doping and diameter of our rod assure good focalization of the pump energy.

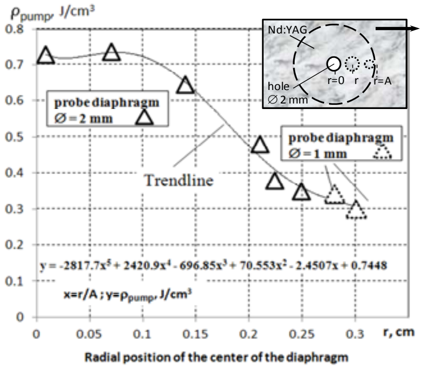


Fig. 2. The pump energy density $\rho_{pump}$ as a function of radial diafragm position (experiment in combination with calculation)

The two-wavelength generation was obtained by introducing EPr and corresponding alignment. The obtained output spot has the specific structure that combined the two generations in coaxial manner. The photograph of the spot is presented in Figure 3 – top picture; at the left the annular spot with stoppedgeneration in the internal channel is shown, and in the right the situation when the two channels operate. In the photograph (Figure 3), the external annular part is formed by the generation in the external rod part at the one wavelength - the strong line 1.06 μm, the internal by the week line at 1.34 μm. The measured energy (FIELDMAX energy meter, Coherent, USA) in the corresponding spot part after spectral separation in presence of the focusing effect and the one calculated for the case of homogeneous pump energy distribution are given in the lower picture.

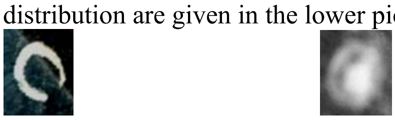

Fig. 3. Actual photograph of the laser spot of the beams emitted from the external part (blocked internal) – left and of the simulataneous operation of the both parts -right

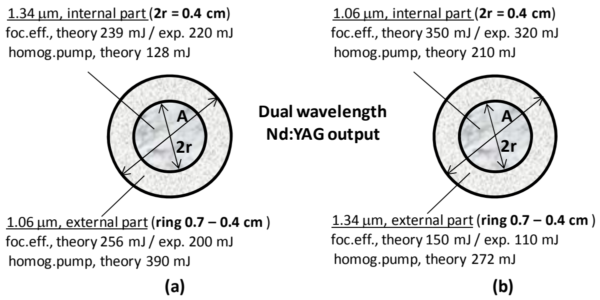


Fig. 4.Output energies in the cross-section of the coaxial output ($2r_i$ = 0.4 cm, A = 0.7 cm). The values indicated, result from theory taking into account the focussing effect (foc.eff.), or homogenious pump distribution and experimental data.

The essential advantages of our coaxial two-wavelength laser technology is the generation the two lines – the strong one and the week one with nearly equal energy output that are evident from the given figure in the left at the right picture. Also, as it can be seen from the photograph, the lasing process uses the full rod volume and the emission is in good coaxial disposition. The temporal investigation shows that the two generations (~250 μs) overlap in time.

An important condition that permits to realize effectively the noted advantages is that the rod works as a high quality focalizing lens. Thus, of an importance is that the side wall of the rod is well polished. The work is possible also with slight frosted wall, however with not perfect focalization and loss of the pump energy. Thus, of interest it is to improve the two wavelength laser operation using the solution with perfectly polished side wall. However, the application of such laser rod creates perfect conditions for the appearance of the non-desired annular parasitic generation due to the obtained closed trajectories, especially in the periphery parts of the rod as a result of the total internal reflection.

As a first point we must define the periphery part of the crystal where it is possible appearance of such generation. Thus we must to determine the part, where it is possible to obtain the close trajectories for the light rays on the base of the total reflection. Lets consider the cross section of the optical homogeneous laser crystal with radius **R**, having coefficient of refraction $\mathbf{n_1}$ (Figure 5) and surrounded by the cooling liquid with coefficient of refraction $n_2$.

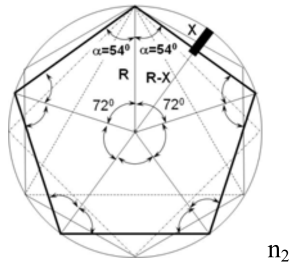


Fig. 5. Schematic of laser rod cross section with a closed equal side polygon.

We must take into account that for the closed ray trajectory in the considered cross section: 1) the angle of incidence $\boldsymbol{\alpha}$ of the ray to the cross point of the radius with the circumference must be higher than the angle $\boldsymbol{\alpha_c}$ for the total internal reflection and 2) the angle of incidence is equal of this one of reflection. After non-complicated mathematical treatment, we find that the trajectory must be equilateral polygon. Lets the number of its side is **N.** We find also that such N side polygon can form closed optical trajectory (i.e. for which can be obtained laser generation). We can obtain for $\boldsymbol{\alpha_c}$, $\boldsymbol{\alpha}$ and N the following relations: $\boldsymbol{\alpha_c} = \arcsin(\mathbf{n_2}/\mathbf{n_1})$, $\boldsymbol{\alpha} \geq \boldsymbol{\alpha_c}$ and $\boldsymbol{\alpha} = 180^o\,[(N-2)/2N]$ with N being the full number.

The last equality permits to obtain the minimal side number Nc of the polygon for closed trajectory for the rays that satisfies the condition $\boldsymbol{\alpha} \geq \boldsymbol{\alpha_c}$ and permits the laser action, respectively.

Thus, the possible annular region of parasitic laser generation is starting from this Nc polygon and can be developed for any other equilateral polygon and N ≥ Nc. It is easy to find that the parasitic generation, that needed of closed trajectory, can appears in the annular part of the laser rod in its periphery between the end of the rod (i.e. the radius R) and the circumferences in the rod cross section with radius (1-X)R, where X = R(1- sin $\boldsymbol{\alpha}$).

For the considered Nd:YAG rod with $n_1$=1.82 and for the typical case of surrounding by the water with $n_2$ = 1.33, it can be calculated X= 0.19 R; i.e. the parasitic laser generation is developed in the periphery annular part of the laser rod between the circumferences with radius R and R-X (between 0.7 cm and 0.19 cm).

This parasitic annular generation will compete with the useful generation along the length of the laser rod in the same annular cross section volume. We treated this competition by applying a modified system of differential rate equations for the considered case:

$$\begin{cases} \dfrac{dN_2}{dt} = R_p(t) - \left(B_1 \cdot q_1 + B_2 \cdot q_2\right) \cdot N_2 - \dfrac{N_2}{\tau} \\ \dfrac{dq_{1,2}}{dt} = Va_{1,2} \cdot B_{1,2} \cdot q_{1,2} \cdot N_2 - \dfrac{q_{1,2}}{\tau_{c_{1,2}}} \end{cases}$$

with $P_{out1,2}(t) = \left(\gamma_1 \cdot c/2L'_{1,2}\right) \cdot h\nu \cdot q_{1,2}(t)$

Here $q_1$ and $q_2$ are the photon number for useful and parasitic generation; $Pout_{1,2}$ – the corresponding output powers, which integration in the time (from 0 to ∞) gives the output energy; the other notation and spectroscopic parameters are given in [11] and in the part II of the present report. The system was solved numerically by Runge-Kuta-4 method.

The solution of the systems for different rod parameters and pump conditions shows that in the considered annular part of the active volume, the parasitic generation in any case suppress the desired useful generation. This leads to the non-negligible loss of useful laser output energy for the annual generation in the coaxial geometry two-wavelength laser. In this manner, in one hand, the well polished rod side wall increases the effect of focusing and thus favoring the phenomena for two-wavelength laser action. On the other hand, this polishing leads to the laser energy loss by the parasitic lasing. Thus, to optimize the laser generation, the parasitic lasing must be suppressed. As a rule, when the laser operates at single wavelength without use of the focusing effect, this practically is obtained by fostering the side wall of the rod. For our case of coaxial geometry two-wavelength laser, as we discussed above, such technique is not convenient.

On the base of our considerations, presented above, we propose to improve the coaxial laser technique via a thin (~ 0.3-0.5 mm thickness) single shearing line at the side periphery along the crystal length with a little depth, slightly deeper than the calculated above X. This will stop completely the appearance of the parasitic lasing and will conserve the good focusing effect. Following our calculations, the depth must be slightly higher than or equal to 0.2 R. For our case of considered Nd:YAG laser crystal, it must be 0.07 cm. The calculated improvement will be for the annular generation of order of 20 %-30 % as the calculations show (depending on the axial division of the laser rod between the two coaxial parts). Such searing, taken into account the described above laser operation using the SPr with a hole, screened ~ few mm of the annular lasing rod part, will provide the negligible effect on the annular laser emission spot.

## III. Conclusion

Here, we have reported the action of the proposed and developed by us new, coaxial geometry, two-wavelength Nd:YAG Quantum Electronic Generator that emits simultaneously and without competition at two lasing lines of the crystal. We have presented its main advantages: 1) permits easily to obtain a laser operation at the weak lasing lines; 2) generation at two lines – the stronger one and the weaker with near equal energies output without loss for equalization and 3) producing the two emissions in coaxial beams, fill the laser rod. If the user disposes with convenient different pairs of end mirrors that are mechanically changeable, it is easily to obtain a tunable line operation. Very convenient design of the two-wavelength, coaxial architecture Nd:YAG laser related to use the well side wall polished rod with a thin , little depth shearing, along the laser rod. The depth X is calculated in this work.

## Acknowledgement

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## References

[1] W. Demtröder *Laser spectroscopy: basic concept and instrumentation*. 3th ed. Springer, Germany; 2003.

[2] V.Vaicikauskasa , Z. Kuprionisb , M. Kaucikasa, V. Svedasa , V. Kabelkaa V. *Mid-infrared all solid state DIAL for remote sensing of hazardous chemical agents,* Proc. of SPIE; pp.6214, 62140, 2006.

[3] R.Farley, P.Dao. *Development of an intracavity summed multiple-wavelength Nd:YAG laser for arugged, solid-state sodium lidar system.* Appl Opt; 34: pp.4269-73, 1995.

[4] M.Nenchev. *Multicolor laser,* Bulgarian patent IIR No25954/reg.38529, 15 June (1978).

[5] I.Levin, A.Chercassov. *Combined Dye solution- Nd:YAG laser. Soviet J. of Appl. Spectroscopy* ; 45(5): 846-50, 1987

[6] H.Aldag, D.Titterton, *From Flashlamp-Pumped Liquid Dye Lasers to Diode-Pumped Solid-State Dye Lasers.* In: SPIE Photonics West;; San Jose, CA; 2005

[7] H. Kisov, M. Deneva, M. Nenchev,. *Development of a tunable, competition less flash-lamp pumped Nd:YAG leser generated of a chosen pair of two lines*. Proc SPIE; pp.8770, 87701Q-1-9, 2013.

8] Song J, Shen D, Liu A, C.Li, ,K.Ueda. *Simultaneous multiple-wavelength cw lasing in laser-diode-pumped composite rods of Nd:YAG and Nd:YLF.* Appl Opt ; 38(24): 5158-61, 1999.

[9] P.Lin, M.Andriasyan, B.Swartz, N.Witherspoon, J.Holloway. *Multiwavelength output from a Nd:YAG-Cr:LiSAF hybrid laser.* Appl Opt.; 38(9): 1767-71, 1999.

[10] W. Koechner. *Solid-State Laser Engineering*. 4th ed. Berlin: Springer; 1996.

[11] O.Svelto. *Principles of lasers,* 5th ed. Springer Science-Business Media, 2008.

[12] R.Ifflander R. *Solid-State Lasers for Materials Processing*. Springer-Verlag; 2001.

[13] Y. Louyer, J. Wallerand, M. Himbert, M. Deneva, M. Nenchev *Two-wavelength passive self injection controlled operation of a diode pumped cw Yb:doped crystal lasers*, Appl.Opt., 42(27): 5463-76, 2003.

[14] G. Lampis, C.Sacchi , O.Svelto. *Pump Energy Absorption in a Ruby Rod.* Appl Opt., 3(12): 1467-70, 1964.

[15] Kretschmann HM, Heine F, Ostroumov VG, Huber G. *High-power diode-pumped continuous-wave $Nd^{3+}$ lasers at wavelengths near 1.44 µm.* Opt Lett 22(7): 466-8, 1997.