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NOVEL RADIO SYSTEMS AND ELEMENTS

YAG:Nd^{3+} Laser Systems for Marine UV Lidar[1]

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Abstract—It is shown that lidar sounding of the aquatic environment by laser radiation at a wavelength of 266 nm provides high sensitivity and reliability of detection of petroleum products. For use in marine lidars, two YAG:Nd^{3+} laser systems (laser-amplifier) with radiation conversion into the fourth harmonic (with lamp and diode pumping) are proposed.

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INTRODUCTION

Marine spectral lidars that probe the aquatic environment with laser radiation in the ultraviolet (UV) range are an effective tool for monitoring the pollution of marine areas and inland waters with oil products [1–3]. Spectral lidars make it possible to detect the presence of oil products at sufficiently low concentrations, outline the area of pollution, estimate the thickness of the oil film on the water surface, determine the type of polluting oil product, and estimate the volume of pollution.

Information about the presence of oil products in the near-surface layer and on the water surface in these lidars is obtained as a result of spectral analysis of the echo signal formed by laser-induced fluorescence of oil products and dissolved organic matter, as well as Raman scattering by water molecules. Typically, spectral lidars use sources of probing radiation in the near UV range: a YAG:Nd^{3+} solid-state laser with radiation frequency conversion to the third harmonic (λ_3 = 355 nm) and XeCl (λ = 308 nm) and XeF (λ = 351 nm) excimer lasers [1–4]. At the same time, for solving the problem of detecting pollution of water bodies with oil products by the lidar method, several advantages are provided by the use of probing radiation in the mid-UV range. Probing with radiation in this range makes it possible to partially separate the fluorescence spectra of petroleum products and naturally dissolved organic matter. In this case, the fluorescence bands of light petroleum hydrocarbons fall into a wide spectral range between the Raman band of water and the fluorescence band of natural dissolved organic matter, in which only petroleum products fluoresce. Recording the excited fluorescence radiation in this spectral range makes it possible to detect and quantify oil products with high sensitivity, accuracy, and reliability.

The optimal source of probing radiation in the mid-UV range for use in marine lidars is a YAG: Nd^{3+} solid-state laser with frequency conversion to the fourth harmonic (λ_4 = 266 nm) [5, 6]. The advantages of using the fourth harmonic were demonstrated in a full-scale experiment performed in the Caspian Sea with the SFPL-24 shipborne lidar [7]. A lamp-pumped LTI-24 pulsed laser (radiation wavelength 266 nm, radiation pulse energy 8 mJ, pulse duration 8 ns, and probe beam divergence 3 mrad) was used as a source of probing radiation. The "oil" echo signals without the contribution of the fluorescence of dissolved organic matter was detected by receiving channels with a sensitivity maximum at wavelengths of 320 and 350 nm. The results of field tests showed that the sensitivity of these channels to the presence of polluting oil products is significantly higher than that of longer-wavelength measuring channels.

The practical use of lidars, which involves their installation on aircraft or a stationary platform, puts forward additional requirements for the technical characteristics of the laser used. First of all, this is a higher energy of radiation pulses, a long service life, vibration resistance, low power consumption and, in some cases, the ability to work at low temperatures.

Taking into account the requirements formulated, a laser system (laser-amplifier) based on a lamp-pumped laser head was fabricated and an optical circuit of a laser system based on two diode-pumped laser heads was proposed. The systems provide generation of radiation at a wavelength of 266 nm and are

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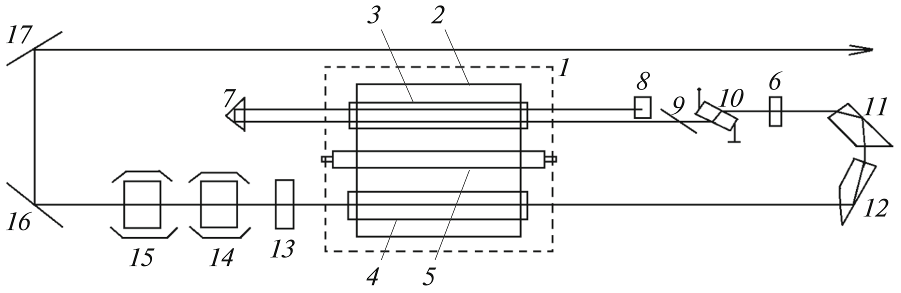

Fig. 1. Optical layout of UV-LPE: (*1*) laser head, (*2*) diffuse reflector, (*3*) YAG:Nd^{3+} active element ∅5 × 100 mm, (*4*) YAG:Nd^{3+} active element ∅6.3 × 100 mm, (*5*) INP-2-5/90 lamp, (*6*) output mirror, (*7, 8*) roof prisms, (*9*) polarizer plate, (*10*) LiNbO$_3$ electro-optical element, (*11, 12*) rotary wedge prisms, (*13*) $\lambda_1/4$ plate, (*14*) nonlinear PTP element in a thermostat, (*15*) nonlinear BBO element in a thermostat, and (*16, 17*) parametric mirrors selecting radiation with a wavelength $\lambda_4 = 266$ nm.

intended for use in marine oil lidars. The paper presents descriptions of these systems.

1. LASER SYSTEMS

The increased energy of radiation pulses is provided by a laser system: a laser amplifier with lamp or diode pumping.

When operating a laser under normal climatic conditions, the most efficient laser system is one that uses a laser head containing one pump lamp and two active elements cooled with distilled water. If it is necessary to work with the lidar in field conditions that allow negative ambient temperatures, it is proposed to use a laser system with two laser heads with side pumping of active elements by laser diode arrays cooled by a frost-resistant liquid such as antifreeze.

The systems use mirror prism cavities, which provide a twofold reduction in the generation threshold due to the additional passage of radiation through the active element and a decrease in the divergence of the output radiation in the critical phase-matching plane of a nonlinear element made of a barium beta-borate crystal (BBO) in the radiation converter to the fourth harmonic [8, 9]. The cavities are resistant to housing deformations and thermal effects in active elements.

As a diode-pumped laser, it was proposed to use the laser presented in [9], which is characterized by a higher pulse energy and lower radiation divergence compared to the known laser [10]. The features of the operation of these systems, including that during transient processes after switching on, are considered.

2. LASER SYSTEM WITH LAMP PUMPING

The lamp-pumped laser system (LPLS) of active elements with the optical circuit shown in Fig. 1 seems to be the most efficient as part of a UV lidar operating under normal climatic conditions.

The high efficiency of the LPLS is ensured primarily due to the following technical and design solutions in the manufacture of the emitter (UV-LPE):

(1) The choice of laser head *1*, cooled by distilled water, with one lamp placed in reflector *2* between two active elements (generator *3* and amplifier *4*), which eliminates the effect of shading pump radiation by lamp *5* when it is transferred to active elements.

(2) The use of prism roof *7* with a rib at the top in the vertical plane dividing the cross section of the active element in half, which ensures a twofold reduction in the generation threshold due to the additional passage of laser radiation to active element *3*, increases the stability of the cavity when a thermal wedge appears in active element *3*, and reduces the divergence of laser radiation in the horizontal plane.

(3) The use of second prism roof *8* as an end reflector with a rib at the top in the horizontal plane increases the stability of the cavity in case of possible deformation of the housing of the UV emitter in the vertical plane.

(4) The use of wedge prisms *11* and *12*, which increase the size of the radiation beam by a factor of 2.25 in the horizontal plane and reduces the radiation divergence by the same factor.

The radiation strength of optical elements of the cavity, as well as nonlinear elements from potassium titanyl phosphate (PTP) and BBO crystals, in which the second ($\lambda_2 = 532$ nm) and fourth ($\lambda_4 = 266$ nm) harmonics are generated, respectively, is high, but turns out to be quite achievable in practice. Therefore, to prevent optical breakdown of the elements, the IR laser should be tuned and operated in the mode of switching on the Q-factor of the cavity after the end of free (peak) generation. This mode is based on introducing losses into the cavity at the beginning of the spike generation pulse and turning on the Q-factor of the cavity completely ~20 μs after the last spike. In this mode, the energy parameters (the maximum energy density in the beam cross section and the pulse energy) and the time parameters of the radiation pulses are sta-

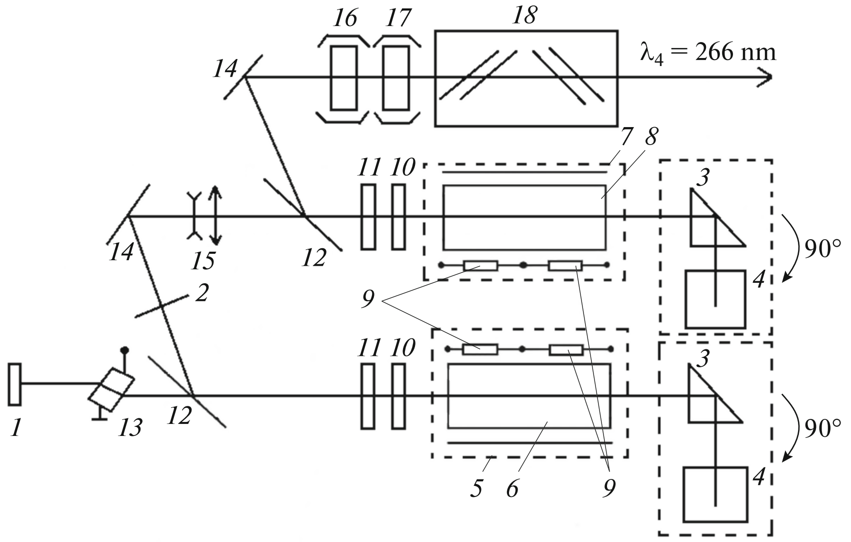

Fig. 2. Optical layout of the UV-DPE: (*1*) blind mirror, (*2*) output mirror, (*3*) rotatable prism, (*4*) roof prism, (*5*) laser head with mirror reflector segment and YAG:Nd^{3+} generator active element ∅5 × 100 mm, (*6, 7*) laser head with a mirror reflector segment with a YAG:Nd^{3+} amplifying element ∅6.3 × 100 mm, (*8, 9*) laser diode arrays, (*10*) quarter-wave plate with $\varphi = 0°$ to the figure plane, (*11*) quarter-wave plate with $\varphi = 45°$, (*12*) polarizer plate, (*13*) LiNbO$_3$ electro-optical element, (*14*) rotating mirror, (*15*) Galilean telescope, (*16*) PTP nonlinear element in a thermostat, (*17*) BBO nonlinear element in a thermostat, and (*18*) stack of glass plates (KU-1 brand).

bilized in a wide energy range of the pump pulses due to the emission of "excess" energy deposited in the active element (population inversion) in the process of spike generation [11].

It is advisable to introduce initial losses into the cavity by deviating the optical *z*-axis of electro-optical element *10* from the cavity axis by a small angle (~2°) within the first ring of the conoscopic pattern, using the element's own birefringence. In this case, the initial losses of the cavity practically do not depend on the temperature of the element. In order to completely "open" the cavity, it is necessary to apply a high-voltage pulse to the electrodes of element *10* from the control unit of the electro-optical shutter (EOS), and the amplitude of the pulse also does not depend on the element's temperature.

The LPLS provides the generation of radiation pulses with $\lambda_4 = 266$ nm with an energy of up to 25 mJ at a repetition rate of up to 30 Hz and a pump pulse energy of 25 J. If the lamp is changed after every 1.8×10^7 pulses, the service life of the system is an order of magnitude higher.

3. LASER SYSTEM WITH DIODE PUMPING

A significant increase in the efficiency of an infrared (IR) laser by reducing power consumption up to seven times is achieved by replacing the lamp pumping of the active element with a diode, in particular, by one-sided side pumping of the active element by laser diode arrays (LDAs) emitting at a wavelength of $\lambda_p = 808$ nm, coinciding with the narrow absorption band of neodymium ions. In this case, the heat release in the active element is significantly reduced and it becomes possible to apply contact heat removal from the active element and LDA housings to a radiator, through which a frost-resistant liquid can be pumped, which does not experience photodestruction due to the absence of interaction with pump radiation [10].

A diode-pumped laser system (DPLS) with the optical circuit shown in Fig. 2 seems to be the most efficient when operating a UV lidar at negative ambient temperatures.

The high efficiency of DPLS is also ensured by optimizing the laser head design and new circuitry solutions in the emitter with diode pumping of active elements (UV-DPE), such as:

(1) The choice of laser heads with one-sided side pumping by monospectral LDAs with improved contact heat removal from laser diodes to the LDA body, which makes it possible to create an inverted population in a large volume of the active medium [10].

(2) The choice of a mirror prism cavity based on the optical circuit of a two-pass amplifier with an end reflector in the form of a roof prism, which lowers the generation threshold and reduces the radiation divergence by a factor of 2 [9, 12].

(3) The choice of a two-pass amplifier with a Galilean telescope makes it possible to increase the output energy of the DPLS radiation monopulses and to minimize the radiation divergence.

(4) The use of prisms and quarter-wave plates in the optical circuits of the generator and amplifier makes it possible to eliminate the depolarizing effects in optical components [10].

A change in the radiation wavelength of laser diodes (LDs) with temperature at a rate of 0.3 nm/C° due to changes in the ambient temperature and self-heating of the diodes leads to the need to use energy-consuming systems for thermal stabilization of the coolant. During transient processes, upon reaching the stationary thermal regime, the LD temperature and, consequently, the pumping efficiency and the distribution of the inverse population over the cross section of the active element change, which can lead to a maximum energy density of radiation single pulses exceeding the maximum allowable level and destruction of the optical components of the DPUV emitter. Using the mode with switching on the Q-factor of the cavity after the end of free generation, which was considered in the previous section for LPLS, makes it possible to exclude this situation. In this case, the lifetime of the DPLS becomes close to that of the LDA (1.8×10^9 pulses).

CONCLUSIONS

YAG:Nd^{3+} monopulse laser systems having laser-amplifier schematics with radiation frequency conversion to the fourth harmonic ($\lambda_4 = 266$ nm) can be built on the basis of laser heads with lamp or transverse diode pumping of the YAG:Nd^{3+} active elements. The choice of the laser head type determines the optical circuit of the emitters. The choice of coolant (distilled water or frost-resistant liquid such as antifreeze) depends on the mode of cooling of pumping sources (lamps or laser diode arrays).

To ensure reliability during the operation of LPLSs and DPLSs in transient modes, it is proposed to use the mode with switching on the Q-factor of the cavity after the end of free generation. DPLS is capable of working with higher energy radiation pulses at higher pulse repetition rates. The advantage of a DPLS is a long service life, low electromagnetic interference level, low power consumption, and the ability to work at negative ambient temperatures. The disadvantages of a DPLS are the necessity of thermal stabilization of the coolant and a high cost of LDAs.

LPLSs and DPLSs can be used in UV lidars for remote detection of oil pollution in water areas.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. E. Brown and M. F. Fingas, Marine Pollution Bull. **47**, 477 (2003).
2. R. Reuter, H. Wang, R. W. Willkom, et al., Adv. Remote Sens. **3** (3), VII (1995).
3. A. Pashayev, B. Tagiyev, K. Allahverdiyev, et al., Proc. SPIE–Int. Soc. Opt. Eng. **9810**, 981018 (2015).
4. V. Pelevin, A. Zlinszky, E. Khimchenko, and V. Toih, Int. J. Remote Sens. **38**, 1967 (2017).
5. Taer Abd Deidan, S. V. Patsaeva, V. V. Fadeev, and V. I. Yuzhakov, Vestn. Mosk. Univ. Ser. 3. Fiz. Astron. **35** (2), 51 (1994).
6. Yu. V. Fedotov, M. L. Belov, O. A. Matrosova, and V. A. Gorodnichev, Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol. 55 (9/2), 105 (2012).
7. A. I. Lyashenko, Yu. A. Gol'din, and B. A. Gureev, Proceedings of the symposium "Measurement methods and mathematical modeling of physical processes: biophotonics, optics and radar," Astrakhan: Triada, 2018, p. 54.
8. A. A. Kazakov, A. I. Lyashenko, and V. V. Strukova, RF patent No. 2325021, May 20, 2018.
9. E. M. Volodina and A. I. Lyashenko, RF Patent No. 204719, Byull. Izobret., No. 16 (08.06.2021).
10. A. I. Lyashenko, E. M. Volodina, S. M. Sapozhnikov, and A. V. Podkopaev, in *Information Technologies and Technologies of Communications. Modern Achievements (Proc. 4th Int. Sci. Conf., Devoted to the 90 Ann. from Date of Basis Astrakhan Univ., 2020)* (AGTU, Astrakhan', 2020), p. 53.
11. A. I. Lyashenko, Fiz. Osn. Priborostr. **6** (3), 38 (2017).
12. V. M. Garmash, E. A. Isaeva, and A. I. Lyashenko, Fiz. Osn. Priborostr. **5** (3), 48 (2016).

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