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Hybrid photodetection module for optical-television underwater imaging systems

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The possibility of creating laser optical television active-pulse underwater imaging systems based on photodetection modules (PDMs) with a sensitive structure of a third-generation electro-optical converter (EOC) with a "blue" GaAs photocathode, sensitive in the spectral range of seawater transparency $\Delta\lambda$ = (400÷550) nm coupled via fiber-optic elements with large-format digital CMOS matrices that enable the formation of video images of underwater objects in scattering seawater, is demonstrated.

Keywords: underwater imaging; EOC; active-pulse system; pulse laser; photocathode; quantum efficiency.

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Introduction

High sensitivity of the third-generation EOC with a “blue” GaAs photocathode in the spectral range of $\Delta\lambda$ = (400÷550) nm is ensured by optimizing the thickness and composition of the buffer layer of the photocathode unit (PCU) of the third-generation EOC. By changing the composition and design of the buffer layer of the PCU, the scientists gained to obtain a GaAs photocathode with negative electron affinity (NEA photocathode) in the composition of PDM samples with a quantum efficiency of up to 30 % at a second harmonic wavelength of 532 nm of a pulsed Nd:YAG laser.

One of the scopes of development of optoelectronic systems for underwater operations related to the search, detection, and identification of unmanned underwater vehicles, sunken objects, as well as the detection of mine danger and sea saboteurs, combating sea terrorism, monitoring pipelines, underwater cables and wells is the creation of optical television systems that provide data on underwater objects not only for the purpose of their detection and location, but also for their recognition and identification by obtaining images.

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Images of underwater objects can be obtained using laser optical television active-pulse underwater imaging systems (APUIS), which generate video images of underwater objects in scattering sea water based on the use of the active-pulse observation method proposed by the Russian Professor A. A. Lebedev in 1936 [1]. The method consisted of illuminating the observed space with pulses of optical radiation with a duration shorter than the propagation time of the pulses to the objects of observation, and in the synchronized reception of optical signals reflected from these objects of observation. This method ensures observation of a limited depth of the surrounding underwater space and sharply reduces the dependence of observation on the illumination conditions of the observed objects and the surrounding backgrounds (overlying water or bottom surface), as well as natural optical interference such as sea water and algae, as well as dissolved and suspended substances of organic and inorganic origin contained in it. Thus, the use of the active-pulse method of forming underwater video images allows eliminating the "parasitic" effect of backscatter interference of the illuminating optical radiation, which is superimposed on the useful image of the observed underwater objects, reducing their contrast and, consequently, visibility range, and often completely losing visibility of underwater objects, especially with reduced transparency of sea water.

The implementation of active-pulse mode technology has led to the creation of devices that provide underwater imaging on a monitor due to combined optical television, laser, and optical technical solutions. The practical significance of the active-pulse mode lies in achieving record-breaking ranges for forming images of underwater objects compared to other optical and optoelectronic devices, including high-frequency sector-scanning sonars operating under identical conditions [2].

The transition to a whole new level of obtaining visual information has expanded the naturally limited capabilities of the human eye for observing underwater objects in the spectral range of sea water transparency, at certain levels of illumination of the underwater observation space, ensuring the observation range depending on the transparency of sea water and allowing the operator to conduct observation underwater in complete darkness even in the absence of solar radiation. This ensures high-quality imaging of distant underwater objects in highly scattering seawater, where the use of standard cameras operating in conjunction with searchlights does not allow to detect and recognize underwater objects.

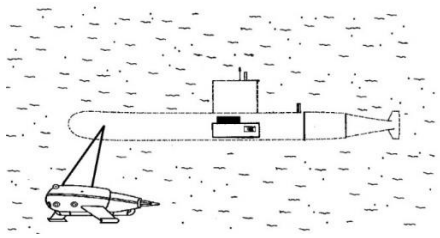
To solve the problem, APUIS can be located on underwater manned and unmanned complexes, remotely controlled underwater vehicles, and other underwater objects (Fig. 1*a*). However, to solve a number of problems, the use of APUIS as part of underwater vehicles is associated with major technical difficulties. In such cases, it is advisable to carry out search and rescue operations using APUIS installed on aircraft (A), e.g., a helicopter (Fig. 1*b*) or unmanned aerial vehicles (UAVs). At the same time, the search time for underwater objects from an aircraft is significantly reduced due to the increased area of coverage.

In this regard, the task arises of forming images of underwater objects and assessing the quality of the image recorded by the laser APUIS through the disturbed air-water interface, which deteriorates mainly due to the influence of the following key factors:

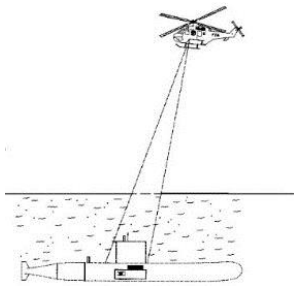
– most of the radiation falling on the sea surface is absorbed and scattered by sea water, which leads to a limitation of the depth of the observed space;

– the reflected signal from underwater objects is very weak, and the background noise of the ocean is high, which directly affects the processing and formation of the image;

– multiple scattering and fluctuations in the distribution of underwater illumination caused by the random nature of the refraction of radiation on a rough surface leads to blurring of the image of underwater objects and disruption of the image topology.



a)



b)

Fig. 1. Schematic diagram of image formation by an active-pulse underwater vision system

To obtain an image of underwater objects and solve the problem of assessing the image quality, the theory of transferring the image of underwater objects through a disturbed water surface and the water column is used. Until now, the main efforts have been focused at establishing analytical relationships between statistically average image characteristics and the conditions of observation of an incompletely averaged image. The task of correctly describing the characteristics of a not fully averaged image can be significantly simplified under the condition that the time of propagation of one probing laser pulse to the observed underwater object and back through the air-water interface, as well as the inertia of the PDM of the optical television recording channel of the system, must be much shorter than the characteristic time of change in the shape of the disturbed sea surface, which can be considered "frozen" during the formation of a single image. With this approach, it is possible to estimate the distortions introduced into the statistically average image by the processes of multiple scattering and absorption of radiation in an aqueous medium and random refraction at a disturbed boundary [2].

Therefore, for the practical use of this method for the detection and recognition from an aircraft of small-sized underwater objects in real time and in conditions of disturbed scattering sea water, the recording channel of the APUIS should be created on the basis of a high-speed PDM, highly sensitive in the spectral range of sea water transparency, and the illumination channel should be based on the highly efficient pulsed laser emitting in the spectral range of sea water transparency.

The spectral characteristic of sea water transmission in the optical spectral range is shown in Fig. 2, from which it is evident that sea water is transparent only in the spectral range $\Delta\lambda = (400 \div 550)$ nm. At the same time, the absorption of optical radiation in the UV spectral range is $\sim 10^9$ times greater, and in the IR spectral region $\sim 10^6$ times greater, than the absorption in the working (blue-green) spectral range [3].

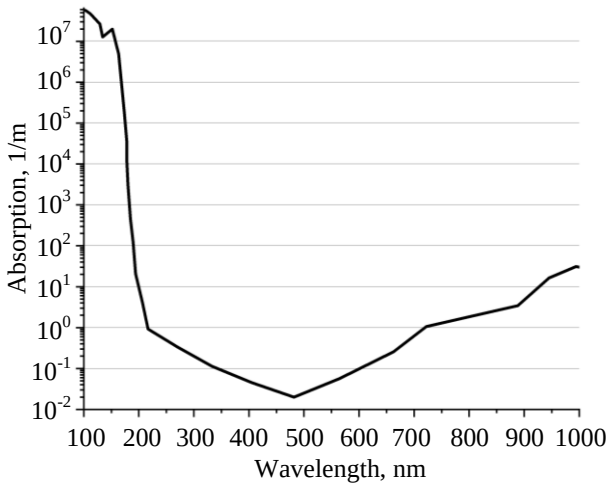


Fig. 2. Spectral characteristic of sea water transmission

Currently, there are no optical television underwater imaging systems on the market

that fully satisfy modern requirements. Therefore, the work on the creation of the APUIS required conducting comprehensive fundamental research to develop fundamentally new technologies and technical solutions that would significantly increase the range of the APUIS installed on an aircraft and improve the quality of the generated image of underwater objects by creating:

- high-speed, high-resolution digital PDMs, highly sensitive in the spectral range of seawater transparency $\Delta\lambda$ = (400÷550) nm;
- high-speed, highly efficient, small-sized pulsed lasers emitting in the spectral range of seawater transparency, used to illuminate various underwater objects;
- a tunable digital controller that generates synchronizing and control pulses sent to the PDM and the illuminating pulsed laser, as well as distributes laser pulses within the strobe according to a specified law, reducing the impact of backscatter interference from natural optical noise on the target observation image;
- specialized computers and software.

The key element that ensures the detection and recognition of small-sized, low-contrast underwater objects in the absence of illuminating solar radiation, at great depths against the background of the seabed and in conditions of a highly scattering aquatic environment, is the PDM specially developed by OAO NPO Geofizika-NV based on a third-generation EOC, sensitive in the spectral range of seawater transparency, coupled with a high-resolution digital CMOS matrix, which will ensure the high-speed formation of multiply enhanced images of underwater objects [4]. OAO NPO Geofizika-NV carried out research on the creation and modernization of active-pulse optical television systems based on third-generation EOC with GaAs NEA photocathode. Fig. 3 shows the spectral characteristics of various photocathodes sensitive in the spectral range of seawater transparency $\Delta\lambda$ = (400÷550) nm [4].

From the given characteristics it is evident that at a wavelength of 532 nm the following photocathodes have sensitivity in the spectral range $\Delta\lambda$ = (400÷550) nm:

– thin multi-alkali photocathode S-20 (up to 15 % quantum efficiency);

– GaAs-based NEA photocathode (at least 25 % quantum efficiency);

– GaAsP-based NEA photocathode (more than 50 % quantum efficiency) [5].

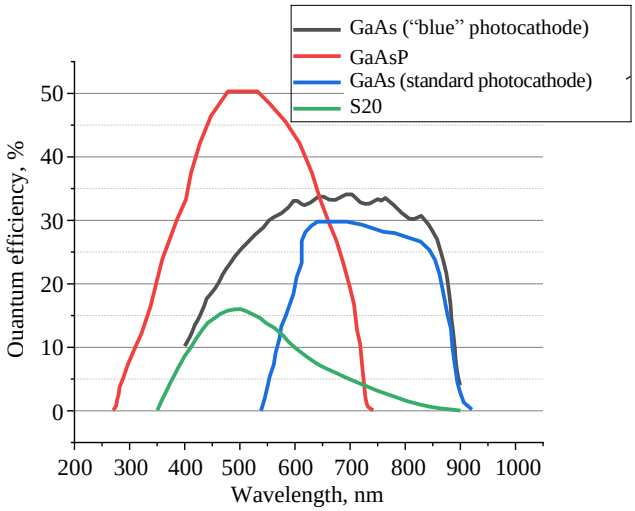


Fig. 3. Spectral characteristics of photocathodes

The analysis showed that the II+ generation EOCs based on S-20 multi-alkaline photocathodes have a number of disadvantages that limit their use in the composition of the ODM for the APUIS:

– firstly, they have significantly lower photosensitivity compared to other types of photocathodes;

– secondly, they have high specific resistance of photocathodes, which will not allow strobing with short pulses (up to tens of nanoseconds).

Fig. 3 shows the spectral characteristics of a standard NEA photocathode based on GaAs, which is intended for third-generation EOC used in night vision devices. Considering that the short-wavelength limit of the NEA photocathode photosensitivity is determined by the thickness and composition of its buffer layer, which is located on the surface of the input window of the EOC in

front of the active GaAs layer, the quantum efficiency of a standard GaAs photocathode at a wavelength of 532 nm is even less than that of the S-20 multi-alkali photocathode.

Currently, OAO NPO Geofizika-NV produces third-generation EOC with standard GaAs-based photocathodes with a $Ga_{0.4}Al_{0.6}As$ buffer layer of about 1 μm and an active GaAs layer of about 1.5 μm. With such a ratio of the thicknesses of the PCU layers, the spectral range of operation of the third-generation EOC based on this PCU is $\Delta\lambda = (590 \div 930)$ nm, and such EOC is intended for operation in night vision devices, in which the sensitivity of the PCU in the blue-green region of the spectrum worsens the operation of night vision devices.

To ensure high sensitivity of the third-generation EOC with GaAs-based NEA photocathodes in the spectral transmission range of sea water (Fig. 2), it is necessary to provide a thin buffer layer of about 0.01 μm in the design of the PCU. However, when manufacturing a PCU with such a thin layer, it may be damaged by mechanical and chemical influences. Therefore, it was decided to produce, in addition to the thin buffer layer, a layer of variable composition (gradient layer) with a total thickness of 0.1 μm.

The design of this PCU structure is shown in Fig. 4. The single-crystal substrate 6 is chemically removed by etching after thermocompression bonding with the glass, and the stopper layer 7 is chemically removed after etching off the substrate 6.

To ensure the matching of the layers of the heteroepitaxial structure of the PCU according to the parameters of the crystal lattice, the maximum permissible amount of aluminum in the buffer layer should not exceed 70 %, which also ensures good optical transmission of the PCU. The thickness of the active layer of the PCU is also of great importance.

Reducing the thickness of the working layer from 1.5 μm to 0.35–0.45 μm reduces unwanted absorption of IR radiation, which reduces the contrast of the image of underwater objects. In addition, the SiO_2 anti-reflection coating with a thickness of about 1.0 nm for the IR region of the spectrum, is not optimal for the blue-green spectral range of seawater transparency, for which the optimal thickness of the SiO_2 anti-reflection coating is about 0.7÷0.75 nm.

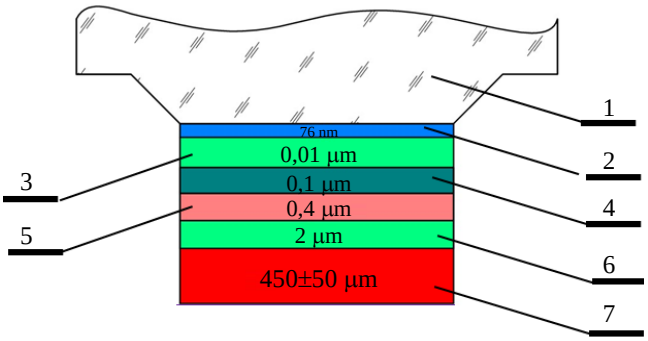


Fig. 4. Schematic diagram of the design of a third-generation EOC PCU with a NEA photocathode based on GaAs. 1 – glass entrance window; 2 – anti-reflection and diffusion barrier layer SiO_2; 3 – buffer layer $Ga_xAl_{1-x}As$; 4 – gradient layer; 5 – active layer GaAs; 6 – stopper layer; 7 – single-crystal substrate GaAs

The discussed remarks have been implemented by OAO NPO Geofizika-NV in the upgraded design of the heteroepitaxial structure of the PCU, the values of which are presented in Table 1, used to create third-generation EOC with NEA photocathodes based on GaAs, which exhibit high sensitivity in the spectral range of seawater transparency. Such EOCs are called third-generation EOCs with a “blue” photocathode.

After the production of the PCU, the process of its activation and assembly of the vacuum block of the third-generation EOC with a “blue” photocathode is carried out in an ultra-high-vacuum final assembly unit (FAU) [4].

Table 1

Seq. No.	Layer name	Layer composition	Alloying level, cm^3	Layer thickness, μm
1	2	3	4	5
1	Anti-reflective diffusion-barrier	SiO_2	–	0.076
2	Buffer	*p*-$Al_{0.7}Ga_{0.3}As$:Zn	5.9×10^{17}	0.01
3	Gradient variable composition	*p*-$Al_{0.7}Ga_{0.3}As$ *p*-GaAs:Zn	5.9×10^{17}	0.1
4	Active	*p*-GaAs:Zn	6.6×10^{18}	0.4
5	Blocking	*p*-$Al_{0.6}Ga_{0.4}As$:Zn	5.9×10^{17}	2.0
6	Substrate	*n*-GaAs:Si (100)	5×10^{17}	450±25

Thermal cleaning and activation of the PCU with cesium and oxygen are carried out in a separate chamber, and the assembly of the vacuum block is carried out in another sealing chamber, which ensures a low noise level and high sensitivity of the PCU.

To obtain a high quantum yield in the required spectral range, the photocathode is activated by filtering the exciting radiation, for example, using colored glass ZS8 or an interference filter.

As a result of the work carried out by OAO NPO GEOFIZIKA-NV, samples of the third-generation EOCs with a “blue” photocathode with a quantum efficiency of up to 25 % at a wavelength of 532 nm were created. The spectral sensitivity characteristics of the created samples of the third-generation EOC are shown in Fig. 5.

Considering that at present the most promising photocathode for solving underwater imaging problems is the NEA photocathode based on the ternary compound GaAsP, the spectral characteristics of such a photocathode from HAMAMATSU PHOTONICS are shown in Fig. 3, and OAO NPO Geofizika-NV is actively working in this direction.

To create an APUIS based on the developed third-generation EOC with a "blue" photocathode, highly sensitive in the spectral range of seawater transparency, specialists at OAO NPO Geofizika-NV have developed a highly efficient ODM of the FPM-5-1 type, in which the third-generation EOC is coupled with a high-resolution and high-speed digital CMOS matrix through a direct fiber-optic element (FOE) to obtain video images [4].

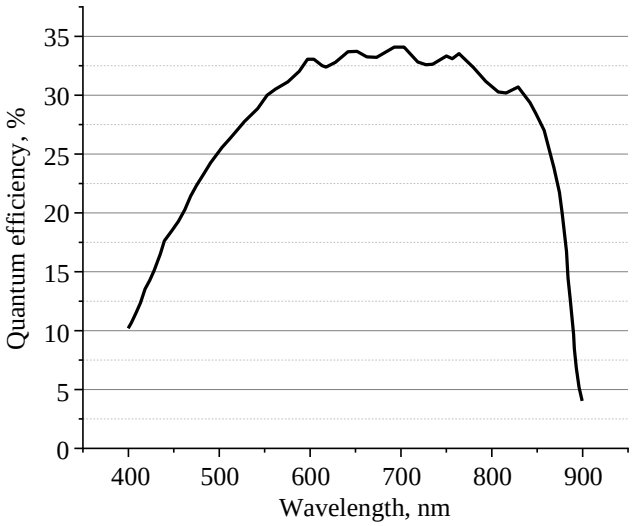


Fig. 5. Spectral characteristics of the third-generation EOC with a “blue” photocathode with a buffer layer optimized in thickness and composition

The main parameters of the developed PDM type FPM-5-1 are given in Table 2.

Table 2

Parameter	Parameter value
Spectral sensitivity range, μm	0.4–0.7
Integral sensitivity, μA/lm	2500
Spectral sensitivity (530 nm), mA/W	150
Working television resolution by field, TVL	450
Maximum frame rate, Hz	100
Signal to noise ratio ($E = 10^{-4}$ lux)	20
Power supply voltage, V	12
Consumption current, mA	250
Output frame format, pixel	2200×1024
Output signal bit depth, bit	12

Fig. 6 shows the external appearance of the FPM-5-1 type module [4].

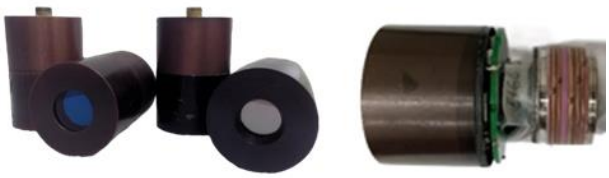


Fig. 6. Appearance of FPM-5-1 type photoreceiving modules and the EOC vacuum block coupled with a camera based on a CMOS matrix

The use of a fiber optic transfer lens results in losses in spatial resolution and energy characteristics of the transferred optical image. The most promising development of the receiving system is the use of designs in which a digital CMOS matrix is placed inside the vacuum volume of the EOC and is excited directly by an electron beam containing information about the image of underwater objects. At the same time, losses are significantly reduced, since there is no focon for image transfer, and the amplification of the electron flow is achieved by bombarding the back side of a specially thinned CMOS matrix. The noise characteristics of this hybrid device are significantly better than those of a traditional PDM Currently, both in Russia, in particular at OAO NPO Geofizika-NV, and abroad, the development of promising hybrid PDMs is underway, which are also photosensitive in the spectral range of sea water transparency.

The active-pulse method of forming underwater images is closely connected with the development of pulsed illumination means, and, above all, with the creation of highly efficient pulsed lasers. The working body is a Nd:YAG crystal. Development of modern highly efficient pulsed lasers. The pumping of the laser's active medium is carried out by diode light-emitting arrays, and Q-switching is performed by an electro-optical shutter. The doubling of the generation frequency (at a wavelength of 532 nm) is achieved by an element based on a KTP (potassium titanyl phosphate – $KTiOPO_4$) crystal, which ensures radiation in the spectral region of seawater transparency (Fig. 2). The developed Nd:YAG lasers provide a pulse duration (at the 0.5 level) of the order of tens of ns with a pulse energy from several hundred μJ to tens of mJ.

An assessment of the average power of laser radiation, carried out by various authors, including during full-scale tests of a model of an underwater imaging camera developed at OAO NPO Geofizika-NV, shows that due to the significant absorption and scattering of laser radiation by a layer of sea water, significant pulse energy and average laser power are required. For each specific application, it is necessary to evaluate the required parameters of the illuminating laser radiation, according to which a specific laser is selected.

Conclusion

The article shows the possibility of creating laser optical television active-pulse underwater imaging systems based on photodetection modules (PDMs) with a sensitive structure of a third-generation EOC with a "blue" GaAs photocathode, sensitive in the spectral range of seawater transparency $\Delta\lambda = (400 \div 550)$ nm coupled via fiber-optic elements with large-format digital CMOS matrices that enable the formation of video images of underwater objects in scattering seawater, is demonstrated.

High sensitivity of the third-generation EOC with a "blue" GaAs photocathode in the spectral range of $\Delta\lambda = (400 \div 550)$ nm is ensured by optimizing the thickness and composition of the buffer layer of the photocathode unit (PCU) of the third-generation EOC. By changing the composition and design of the buffer layer of the PCU, it was possible to obtain a NEA GaAs photocathode in the composition of PDM samples with a quantum efficiency of up to 25 % at a second harmonic wavelength of 532 nm of a pulsed Nd:YAG laser.

Further improvement of the APUIS can be associated with the development of NEA photocathodes based on the GaAsP structure, which currently has a quantum efficiency of up to 50 % at a wavelength of 532 nm [5].

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