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Photonic Technologies in Space Device Engineering

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Abstract. The article provides an overview of the basic technologies where products of photonics and optoelectronics are used or potentially can be used to create a target and service equipment of navigation, communication, and Earth remote sensing space-craft. The possible range of technology solutions needed to ensure precision satellite positioning, creation of optical communication technologies used for information exchange on the lines of "spacecraft-spacecraft" or "spacecraft-Earth", as well as the choice of ma-terials for photodetectors and measuring sensors is presented. Moreover, technological trends of modern and advanced developments based on the use of photonic technologies, providing record characteristics that meet the global standards in the development of space device engineering are shown. The main recommendations for the development and intensification of the introduction of photonic technologies in the space industry of the Russian Federation are given in the conclusion.

Keywords: Photonics, optoelectronics, fiber optics and optical communications, onboard time scales, coordinate-time and navigation support, frequency instability, optical frequency standards, small-sized atomic clock, optical gyroscope, annular resonator on "whispering waves", photoelectronic receivers, hyperspectral devices, photon sensors

Introduction

Photonics in recent years has become one of the important directions in development of innovative economy in different countries. The development of this high-tech area is considered a priority for the global aerospace industry. NASA [1,2], ESA [3], JAXA and space agencies of the BRICS countries [4] identified this trend in the national programs of development of advanced space systems and complexes for various purposes as a priority.

The emergence of photonics as a scientific field, encompassing problems of generation, collection, dissemination and processing of optical signals, in itself marked a strong potential for the introduction into the information systems created for different purposes, used in various industries.

Despite the fact that the space industry does not have large amounts of commercially available high-tech products, the industry itself can certainly become the locomotive for the introduction of modern photonic technologies into the space complexes and systems under development. This circumstance is due to the fact that the functioning of space-based information systems for various purposes is provided by the processes of generation, emission, reception, processing and transmission of electromagnetic signals throughout the electromagnetic spectrum, from ultraviolet optical to microwave radio band.

Constantly growing volumes of data produced by space systems, as well as the requirements for miniaturization of target and service equipment for spacecraft, define the urgent need for the developers to search for promising technologies used in space device engineering for creating new types of target and service equipment.

The demand for implementation of photonic technologies is increasing in space applications, since with increasing volumes produced by space data facilities, the infrastructure for generating, collecting, processing, digestion and dissemination of optical data to the end user rests on purely physical limitations associated with the use of electrons as the information carriers. Photonics is the direct successor to the electronics [5]. Its main difference is that in place of electrons, photons are used as information carriers. Nevertheless, the development of photonic technologies largely repeats the stages of development of electronics. Today, photonics combines areas such as optical photonics, microphotonics, nanophotonics and radiophotonics, covering the range of the electromagnetic spectrum from UV to microwave.

In [6] it is shown that in the future remote sensing systems, the amount of generated data on board the spacecraft will increase by at least three orders of magnitude due to the increase in the spatial resolution of the target imaging equipment to the submeter size and the use of several thousand spectral channels of survey. The currently employed on-board computing power will not be sufficient to collect, process and exchange data without the use of photonic technologies.

Note that the functionality usually implemented with one “big” spacecraft, complexing a large number of target devices, in the future can be distributed among a certain number of interacting with each other “small” spacecraft [7]. Each spacecraft in such groups developed on the principle of “companion device” may have different limited functionality, but, on the whole, the cluster will function as a single unit. At the same time, in order to maintain the secure borders for each of the interacting elements, joint control and synchronization of spacecraft maneuvers within the cluster is required.

Optical inter-satellite links are a great tool for solving problems of interaction of the elements of such a distributed system, especially in view of the need to transfer large amounts of data from each party [8]. For the components of this distributed spacecraft to act as the “main server” and “router” a link with a capacity of not less than several Gbit/s is required [9].

When designing a spacecraft for deep space exploration, it is necessary to create the on-board equipment that meets the extremely stringent requirements for weight, power consumption and the geometric dimensions. Therefore, the large and power-inefficient antenna complexes are based on the ground to compensate for the limitations imposed on the on-board equipment of the spacecraft. In accordance with Article [10], the optical communication terminals are lighter than the traditional radio systems. Provided a repeater station is installed on the ISS or other spacecraft (outside the Earth’s atmosphere), optical communication can be used for control, as well as for the target channels of communication with spacecraft designed for deep space exploration.

Creating data transmission hardware in the optical range of the spectrum in the long term will almost completely solve the whole complex of the current problems. On the one hand, there is a technical possibility to considerably (at least by an order) increase the bandwidth of on-board radio lines, on the other hand, several devices can simultaneously operate in the optical range without compromising their functionality [11] due to the absence of electromagnetic compatibility problems.

Modern space systems and complexes used for a variety of national economic goals, actively employs the methods and tools for measuring the time and frequency characteristics of the signals detected by them. In [12] it is noted that since time and frequency are the most frequently measured physical quantities, one of the main applications of modern metrology, ensuring the proper functioning of satellite equipment, is the creation of standards of various physical quantities on the basis of the fundamental physical constants (FPC) and precision frequency measurements.

The relative instability of the on-board frequency standards used as a part of the on-board spacecraft equipment, significantly impacts the accuracy of satellite-based positioning of ground targets. Existing tools with an instability of around 10^{-14} make it possible to establish the coordinates of objects with meter accuracy. The transition to the centimeter or millimeter accuracy requires the use of on-board standards of time with an instability better than 10^{-16}. Such precision will be ensured by the optical atomic frequency standards currently under development both in the Russian Federation and abroad.

Thus, the precise metrology of frequency and time measurements is vital to make progress in the following space applications [13]:

– basic research, using precise measurements of distances;

– communication, including space communication, using high speed data transmission over long distances;

– global satellite navigation systems GLONASS/GPS, requiring accurate measurement of time.

Optical-electrical (photonic) components have been widely and for long implemented in modern space systems of remote sensing as photosensitive detectors, as well as in solar batteries, providing power to spacecraft. In addition to these obvious applications, the developers of space systems show an increased interest in the use of photonic technology in carrying out various measurements on board the spacecraft, as well as for the collection, processing and transmission of measurement information obtained.

Paper [14] provides an overview of the storage systems and devices for large volumes of digital data, including CD drives and photonic data storage devices based on the use of holographic methods.

According to the report presented by the International Data Corporation (IDC) in 2011, the total amount of data generated globally is growing exponentially and will reach 35 ZB by 2020 (1 zetabyte (ZB) = $5*10^3$, 1 exabyte (EB) = $5*10^6$, 1 petabyte (PB) = $5*10^{12}$GB) [15], while, for example, only the amount of data from a daily survey of the Earth surface with sub-meter spatial resolution of potential space-based systems [16] could make $5*10^{14}$ digitized points or over 10^{15} bytes = 10^6 GB or 73 EB yearly. It is noted that the provision of storage of such data volumes is only possible when using new photonic principles underlying the development of advanced means of data storage.

One of the earliest publications on the use of photonic technologies in spacecraft [17] declares the need for a wider band of frequencies for information signals, their on-board processing in the harsh conditions of the outer space, and makes serious demands to improve the technologies of creating an electronic component base and new materials.

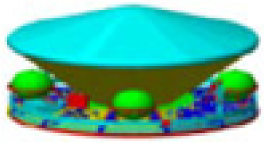
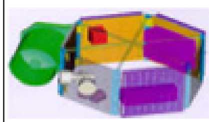
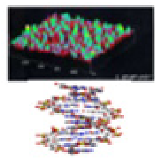
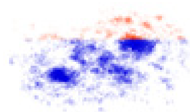
The purpose of this article is to analyze possible areas of application of photonic technologies in the development and creation of future equipment for space-based information systems and complexes for various purposes, to identify the main problematic issues, as well as to formulate the recommendations and proposals for their solution.

Assessment of global trends in the use of photonic technologies in space systems of communication, navigation and remote sensing

The first employment of photonic technologies for space applications included radio signal distribution circuits, delayed signal lines, on-board frequency generators, analog-to-digital conversion with the photonic signal processing, as well as fast analog-to-digital signal conversion. Along with the listed areas of space applications of photonic technologies, the employment of nanophotonic components has been started to create advanced designs of space technology [18].

To implement technically exigent mission of deep space exploration at an acceptable cost, NASA has developed a special technology program known as X2000. The program implied that beginning with 2000, every two or three years the upgraded subsystems, as well as

Table 1. Roadmap of spacecraft avionics until 2030

	Descent module of the “Mars exploration” mission	1st generation X2000	3rd generation	5th generation	Future
Volume, cm^3	50000	10000	1000	10	1
Mass, kg	80	40	1	0.01	0.002
Power consumption, W	300	150	30	5	0.05
					
Year	1999	2003	2010	2020	2030

Source: Nanotechnology Research Directions: IWGN Workshop Report, Vision for Nanotechnology R&D in the Next Decade, September 1999.

elements of the spacecraft design, will be developed and implemented. One of the objectives of the program was a significant reduction in the size of the spacecraft avionics with each new generation of X2000 products, partly through the implementation of the nano- and microtechnologies. Table 1 contains the road map of development of spacecraft avionics, which shows that the projected volume, weight and power consumption of avionics has reduced by about one order of magnitude in the last 10 years. The parameters of Martian spacecraft avionics as of 1999 are taken as the base level.

Notably, even the first upgrade in the framework of X2000 is an integrated avionics system that combined command telemetry and data processing functions, attitude control, energy distribution and management, as well as the interface of the scientific payload. The use of automated technologies of development and design of equipment has made it possible to create a highly integrated modular block architecture, which provided a greater degree of design reliability for long missions in deep space.

Currently, great hopes are put on the use of the “system on chip” technology, that allows in the future to create of avionics modules in a single chip – an integrated circuit. At the same time such a crystal may include power consumption management, sensors and telecommunications modules, combined with the on-board computer and memory. Today’s success of the global space device engineering fully confirmed the predictions given.

The goal set for 2020 involves the development of revolutionary computer technology that could not only overcome the limitations of a simple scaling of semiconductor technologies, but also make the concept of “intelligent spacecraft” feasible. Such a spacecraft should be a fully self-contained, highly integrated spacecraft with superb capabilities and ultra-low power consumption. To achieve these goals it is necessary to ensure the widespread use of photonics technology in general and nanophotonics in particular. This circumstance is due to the fact that the phenomenal advances in digital computer technology in recent years, even using supercomputers, will not be able to compete with biological systems in the accomplishment of such ill-conditioned tasks as image recognition, processing of multisensor systems data, fail-safe control, and adaptive adjustment for environment conditions.

Creation of new multifunctional materials based on quantum technologies with extraordinary properties will allow to achieve a faster (tens of Tbit/s) data transfer, secure storage and processing of information, replacement of the hardware components of microchips, as well as space and transport equipment.

The use of the next generation microphotonic integrated circuits permits the integration of various optical components into a common photonic chip, which minimizes the number of external connecting optical fiber cables and reduces the overall size and weight of a space system, at the same time substantially increasing its reliability.

Table 2. Interests of the European space industry in the use of photonic technologies and metamaterials

Technology	Technology level	Development horizon	Priority	Usage
Photonics-on-chip	Level C	Medium-term	Highest	Protection against radiation, communication
Photonic FOCL	Level C	Medium-term	High	Devices, radiation resistance
Aerogel packaging of photonic components	Level C	Long-term	High	Thermal protection
FOCL on sapphire	Level C	Medium-term	High	Temperature control
Microresonators	Level A	Long-term	High	Spectroscopy
Nanocrystals	Level A	Medium-term	High	Sensors
Photon beacon	Level B	Medium-term	High	Spectroscopy
Vector vortex coronagraphy	Level C	Medium-term	High	Detectors
Infrared metamaterials	Level A	Long-term	High	Cyclic changes in temperature
Metasurfaces	Level A	Long-term	High	Sensors
Interferometer with tunable pupil	Level B	Medium-term	High	Interferometry
Quickly tunable metamaterials	Level A	Medium-term	Highest	Communications, sensors, detectors
Frequency selective surfaces	Level A	Medium-term	High	Design of antennas, sensors, detectors
Plasmonic enhancement of photosensitivity	Level A	Medium-term	Highest	Sensors, detectors
Frequency selective surfaces	Level A	Long-term	High	Cyclic changes in temperature
Metamaterials with a negative index	Level A	Long-term	High	Detectors
Phase changing films	Level A	Long-term	High	Radiation protection
Flat tunable lenses	Level A	Long-term	High	Sensors
Plasmonic color separation	Level A	Long-term	High	Sensors

Source: Technological Breakthroughs for Scientific Progress (TECHBREAK)// Brussels, ESF Forward Look, 2014.

In [19] the interests of the space industry in Europe have been identified in the field of photonic technologies and metamaterials, which are listed in the Table 2. It gives expert assessment of the current level of readiness for each technological trend. The level A corresponds to TRL 1-3 of the standard scale of technology readiness [20]; level B corresponds to TRL 4; level C, to TRL 5.

Thus, for all these technologies and their applications, the main advantages of photonic systems that make it possible to successfully use them in space missions through a combination of built-in micro-, nano- and fiber optics, include:

– low susceptibility of the systems under development to electromagnetic interference, electrical discharges and the impact of charged space particles;

– a significant reduction in the weight of signal lines (<1/20 compared to traditional cable electrical connections);

– high throughput data transfer capability (up to tens of THz);

– galvanic isolation of critical subsystems of spacecraft (SC);

– high-speed processing of optical, radio and microwave signals;

– high-speed transmission/reception of useful information;

– sensitization and expansion of operating ranges for sensors and detectors;

– increase in the active life time of SC.

The realization of such benefits and the application of photonics products in the on-board spacecraft equipment dramatically improves the performance:

– reduce the weight of the signal cable lines by 20 times;

– reduce electric power consumption by 30%–50%;

– increase the speed of information processing by 20–200 times;

– reduce the cost of the equipment manufacturing by 20%–50%;

– increase the active lifetime of space devices by 1.5–2 times.

Based on the analysis of these photonic technologies and their applications in space devices, critical photonic technologies, topical for the Russian space industry can be identified:

– infotelecommunication technology (optical inter-satellite links and downlinks, fiber optic and wireless information networks inside the spacecraft, hybrid computing devices);

– remote sensing technology (receivers of optical and infrared signals, optical aperture synthesis);

– technologies of development and implementation of sensor, measuring and converting devices (temperature and pressure sensors, accelerometers, ADC/DAC, optical accelerometers, optical gyroscopes, solar sensors);

– quantum calculators technology;

– optical laser detecting and ranging systems technology;

– technology of small on-board transceiver antennas made of metamaterials;

– wireless power transfer technology;

– information storage technology, holographic memory;

– quantum technology of satellite navigation and orientation systems (compact on-board atomic clocks, optical accelerometers, optical gyroscopes, solar sensors, terrestrial radiation sensors).

We now estimate the current state of development of photonic technologies for space applications and the main trends of their development.

Basic requirements for the emerging technologies of satellite navigation through the application of photonic technology

The final report of the US National Security Space Management "National Positioning, Navigation, and Timing Architecture Study" [21] presents the development trends and recommendations for the assessment of development alternatives of PNT systems. The development team, challenged with the task of identifying potential tools and technologies for solving future problems of PNT, have used the procedures accepted in the US National Security Space Management that take into account any non-standard ideas that now may seem extreme or unusual, but by 2025 can become feasible. The analysis shows that the most promising are the 3 technologies that can lead to significant changes:

– Chip Scale Atomic Clocks (CSAC)

– high-precision optical atomic clock;

– cost-effective units of inertial sensors based on microelectromechanical systems (MEMS) – extremely high-precision interferometric inertial navigation systems, etc.

The total scope of the experiment covered 50 technologies of which the following areas were selected as priorities for the development of global navigation systems:

– the use of small-sized atomic clock;

– the use of optical clocks based on atomic transitions at optical frequencies;

– installation of laser retroreflectors on all spacecraft and the use of ground-based laser tracking in order to improve the satellite orbit models to enhance the accuracy of determining the orbit parameters;

– precise calibration of devices that transmit time signals, including the equipment on-board the spacecraft, transmitting the information about the time in the navigation signal;

– communication of the elements of GNSS through inter-satellite laser data channels;

– provision of additional sources of airborne PNT;

– the formation of timing support tools, that transmit timing information over the fiber optic link;

– creation of a single GNSS service that could provide centimeter accuracy in real time or close to it, and millimeter accuracy in post-processing mode, as well as the integrity data in real time;

– the organization of high-precision ephemeris timing support for the consumers using all available signals for navigation tasks.

Using the radiation of pulsars for synchronization of satellite navigation systems

The accuracy of mutual synchronization of satellite navigation systems is influenced by three main factors:

– the accuracy of the system time scale itself, which is determined by the technology of its realization: the stability of its constituent time keepers, methods of their comparison and the creation of the group time scales;

– synchronization accuracy of the on-board time scales (OTS) and the system time scale is determined by the technology of the synchronization process;

– the accuracy of prediction in consumer equipment on-board time scales for a predetermined interval, that is determined by the stability of the on-board clock device based on the on-board frequency standards with specified accuracy characteristics.

One of the possible development directions of time synchronization of satellite navigation systems in the long term is its building on the basis of a pulsar time scale, actively developed in recent years both in Russia and abroad [22, 23]. A detailed overview of various methods of navigation in deep space is discussed in [24].

The idea of using a highly stable pulse repetition observed in pulsar emission at virtually unlimited space-time extent by transforming it into a reference (pulsar) time scale arose almost immediately after the discovery of pulsars in 1967. The relative instability of proper rotation of pulsars is 10^{-14} and higher at a time interval of several years. The best value is shown by the pulsar J0437-4715 with an instability of $\sigma_y(\tau) < 10^{-15}$ on a time scale of over 3 years (unpredictable deviation is 10 ns in 3 years). Thus, the stability of a pulsar time scale (PTS) is potentially high and essentially can be used for highly stable and precise timing.

The pulsar based scales, however, have several advantages compared to the existing atomic time scales:

– the means for a reliable observation of the source with the existing or future astronomical instruments with the accuracy sufficient for the tasks of potential consumers;

– the lifetime the source, sufficient for the customer requirements (depending on the task);

– high-precision extrapolation of the pulse arrival times by the analytical model (high stability of the observed emission period, or predictability);

– shorter radiation period than required for the consumer time scale synchronization;

– a high degree of recognizability of electromagnetic radiation variations.

Studies, including those conducted in Russia, have shown that, due to the presence of a sufficiently large number of bright stable pulsars, it is possible to build a pulsar group time scale based on their observation, with higher stability than that of each of its constituent individual pulsars. The stability of a pulsar group time scale is estimated to be in the order of 10^{-16} over long periods of time (years, decades), which is much more reliable than existing nuclear group time scales.

In this context, the future competitiveness of the PTS in comparison with the atomic time scale it is of considerable interest. The question is very important owing to the fact that the development of ground-based atomic frequency standards is rapid, and during the last 50 years their stability was improved by about an order of magnitude every 7 years. Now they have characteristics comparable to the stability of the very stable pulsars. For example, the most massive cesium clock of the 5071A type, used for the creation of the TAI global time scale, has an instability of $\sigma_y(\tau) \leq 5\times10^{-15}$ in the sampling intervals of 72–120 hours. The instability of the clock based on the best hydrogen masers with a sampling interval of 120 hours is $\sigma_y(\tau) \leq 5\times10^{-16}$. The group time scales (TAI, UTC) are even more accurate: according to the results received from 220 atomic clocks from almost 50 time laboratories around the world, those scales have an instability of about 2×10^{-15}.

Spaceborne optical time standards

Optical atomic clocks will be widely employed both in ground and in spaceborne segments of global navigation satellite systems, which will improve the accuracy of the spaceborne time standards by 2–3 orders of magnitude. This, in turn, reduces the need to update the satellite time standard parameters and thus improve the autonomy of navigation satellites. With better understanding of the influence of the atmosphere on the passage of the navigation signal this will eventually lead to a significant increase in the accuracy of positioning systems for consumers.

A detailed review of the application of the European research results in the field of satellite navigation is presented in [25].

The work on optical atomic time standard provides guidance on the parallel development of four different variants of optical atomic clocks [26]:

1. Optical atomic clocks with ion baffles based on 88Sr+ [27].
2. Optical atomic clocks based on strontium atomic lattice [28].
3. Optical atomic clocks with ion baffles based on quantum logic using 27Al+.
4. Optical atomic clocks based on the mercury space lattice.

The development of these devices is expected to be performed in broad international cooperation of companies from the European Union countries, including the UK, Germany, France, Austria, Italy and Switzerland that hold the leading positions in the optical radiation metrology. Certainly, professionals from the companies specialized in space system integration should be involved in these projects from a very early stage.

Small atomic clock

Development of small-sized optical frequency standards lies in line with the miniaturization of the lasers used for these purposes. Such research projects first took place in the National Institute of Science and Technology (Boulder, US) [29]. Similar projects are under way, in particular, at the Institute of Laser Physics SB RAS [30] ("generator of optical frequencies based on femtosecond forsterite laser"). The size of the laser developed here is 20 by 30 cm; the ILP I2/532 – 1 optical frequency standard is created on its base. Together, LPI, Fiber Optics Research Center, and the Avesta company (LPI subsidiary) were the first to develop a compact femtosecond optical clock, capable of operating on board of an artificial satellite after the necessary fine-tuning (stability of 10^{-14}).

To date, the efforts in the field of optical frequency standards are for the most part on the stage of research and advanced development; the commercial use of such devices is limited. It is believed that under the condition of overcoming their inherent shortcomings such equipment will have a very positive market outlook.

Main research areas in the field of optical communication systems

In general, studies of the open lines of the optical range are aimed at solving problems in several areas. Finding the optimal bands for data transmission in the atmosphere, as well as factors affecting the speed of data transmission, are the goals of many research projects. The possibilities of increasing the transfer rates and development of new signal modulation schemes are studied [31]. Transmitters and receivers of optical signals are being developed [32]. Analytical research, justifying the need to introduce optical technologies to replace the traditional radio engineering, also plays a major role.

The idea of information transmission in the optical range was proposed in the 1960s [33]. Specialists of the Hughes Corporation proposed to use for this purpose the newly developed rubidium laser. Subsequent experiments have had little success over the following 50-60 years. Only in the beginning of the 21st century the first space experiment on the transmission of information in the optical range, SILEX, was held [24].

In 2001, as a part of the SILEX, information has been transmitted from the low-Earth orbit (SPOT-4 spacecraft) to the geostationary orbit (ARTEMIS spacecraft). Transfer rates of up to 2 Mbit/s at the 819 nm wavelength have been achieved [34].

Simultaneously with the transfer of information in open space with the ARTEMIS spacecraft, the information transmission through the atmosphere was carried out. In 2001, data rates up to 50 Mbit/s through the 847 nm channel were also achieved. Presently, data rates as high as 5-6 Gbit/s have been achieved. Such an optical link functions aboard the TerraSAR-X and NFIRE spacecraft using the 1064 nm channel.

For transmission of information in the optical range modern equipment uses two frequencies, which lie in similar atmospheric transparency windows: 1064 nm (282 THz) and 1550 nm (193 THz). For optical satellite links the 1550 nm channel seems more preferable than the 1064 nm channel, as the background noise in this channel is 4 times lower. In addition, the turbulence, which increases the signal-to-noise ratio, has less effect [36].

At present, the possibility of creating optical terminals with speeds from 30 to 100 Gbit/s is considered. Preliminary calculations show that the aperture of the "mirrors" of such terminals will be 200 mm and 1000

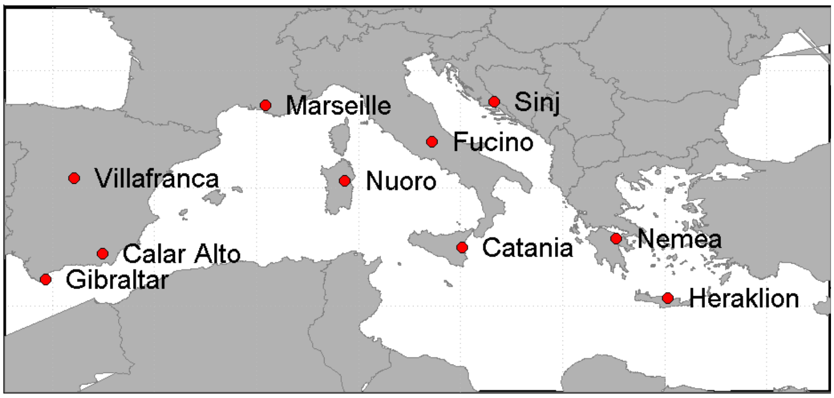


Figure 1. Prospective placement of the European terrestrial optical stations network
Source: Adapted from [31].

mm respectively. In accordance with the energy budget of the radio link, it can be stated that the minimum viewing angle must be at least 30° above the horizon, without the use of antinoise signal coding technologies [31].

Work [31] shows the results of an experiment on information transmission in the optical range in the atmosphere at a rate of 1 Tbit/s. It is shown that information can be transmitted and received at such transfer rate, but the transmission distance does not exceed a few hundred meters. This study examines the possibility of using the new technology of Erbium-Doped Fibre Amplifers (EDFA), which may increase the characteristics of both the receivers and the transmitters of optical signals. In addition, it is proposed to consider the possibility of multiplexing of the channels with different wavelengths, which will increase the energy potential of the optical line.

It is well known that the ability of the optical data transmission lines is limited by the presence of clouds in the path of the optical signal. The European Union established a geographically distributed network of stations, which provides spatial diversification of the receivers and is the most reasonable way to ensure the continuous availability of the communication channel. Along with the spatial distribution of the receivers (by analogy with conventional radio systems), research is conducted in the field of multiantenna receiving stations, which are meant to reduce the traffic of optical lines in order to increase the system capacity [37].

Possible distribution of ground stations in Southern Europe is shown in Figure 1 (10 stations) [31]. The following reasons (alongside with cloudiness) can result in the lack of communication: strong turbulence in the atmosphere above the receiving station, the presence of the sun in the area of visibility, the technical condition of the station or of safety considerations (for example, the presence of aircraft in the signal propagation path). This cloudiness is still the dominant cause.

The average annual availability of this network, which is determined by the probability that at least one station is not obscured by clouds and is available for the exchange of information, is 99.89% [31]. A detailed statistical analysis of the cloudiness in Europe shows the situation when all the stations are covered by clouds may occur mainly in winter, i.e. to further increase the percentage of availability, one station must necessarily be placed in the southern hemisphere.

One of the main problems in the construction of space optical communication systems is to provide a technology for the data transition from one ground station to another directly in the course of a session. To prevent data loss when switching, it is necessary to provide a data feed to the stations, at least as long as the data stream is not synchronized.

The technology can be created with the application of the duplicated line, which implies the presence of two transceivers on board of the geostationary spacecraft. Such apparatus may be arranged in the form of two independent terminals or as a single telescope with an enhanced focal plane in order for two stations to be multiplexed. Furthermore, for the successful implementation of this technology, the information about the actual and forecasted availability of ground stations, taking into account all factors (clouds, turbulence, etc.), is required.

The use of optical links for the transmission of information from spacecraft has some fundamental advantages over the conventional radio technology. Namely, higher large data transfer rates and smaller apertures of

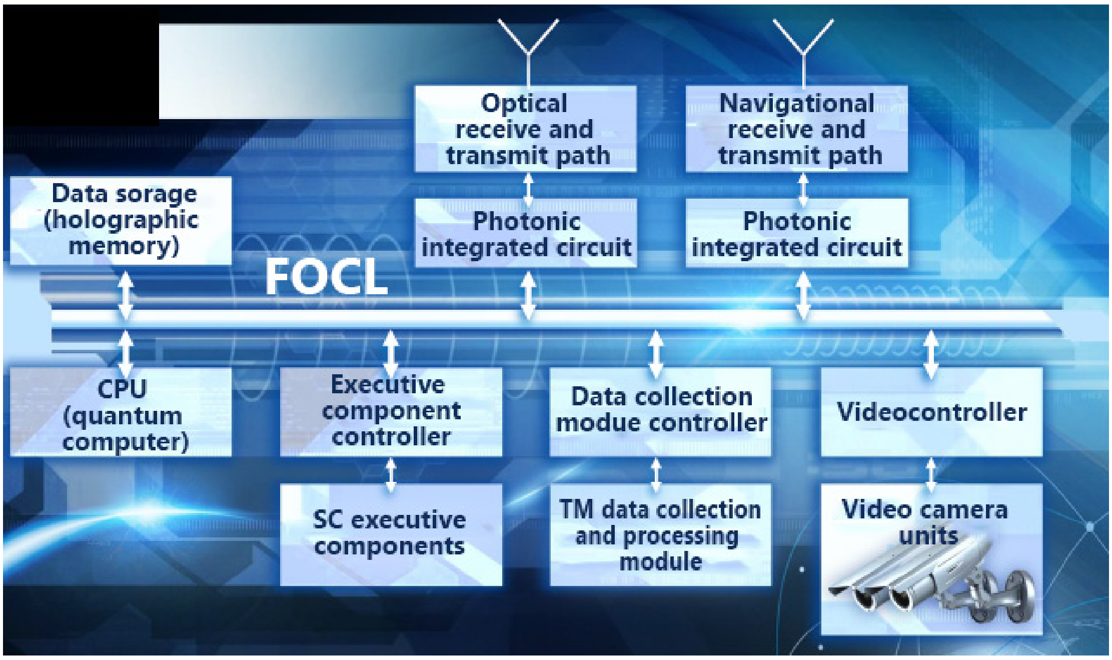


Figure 2. A generalized block diagram of the SC information system

the transceiver complexes. These factors increase the effectiveness of such solutions.

In the open space the problem of cloudiness is absent and, therefore, an alternative approach to the data transfer implies that the data from low-orbit satellites can be broadcast through the optical channel to a geostationary satellite, which will transmit the data to a ground station in the radio frequency range, which is not obstructed by the atmosphere.

Key research areas for the application of photonic technologies in the target and service equipment for space information systems

Now let us consider the basic technology of building the information infrastructure of space information systems.

The block diagram of the on-board segment of space information system is shown in Figure 2.

It is seen that the number of data connections in the space information system is large and includes both the data transfer within satellites and the SC-SC and SC-ground communication links. As the complexity of the equipment increases, the amount of information grows exponentially, and this fact becomes a bottleneck for space device engineering.

Photonic technologies, specialized for space applications, are used to create a wide range of payloads and service systems of the spacecraft:

- fiber optic gyroscopes;
- integrated micro- and nanooptics;
- photodetectors for visible and infrared ranges;
- acoustic and optical filters and dispersive elements;
- diffraction antenna arrays;
- small antennas based on metamaterials;
- high-frequency micromechanical and electro-optic modulators;
- organic energy converters;
- radiation-resistant ECB of the new generation;
- magneto-optical holography products;
- microelectronics element base with on-the-chip elements of photonics-based galvanic isolation.

Work [41] indicates that the optoelectronic components are increasingly used in Earth remote sensing missions due to their high integrability and the ability to provide better performance while reducing weight and dimensions of the target devices, as well as improve the quality of the images of the Earth's surface. However, the technology readiness level of innovative technologies is not always sufficient for use in the engineering development, which leads to unnecessary risks that must be considered at the earliest stages of development. The cited paper also attempts to identify these risks and propose the ways to reduce them.

It is noted, that during the development of the Pleiades space mission, a number of fundamentally new optoelectronic technologies were implemented, which provided a new level of the total system performance for the time. The characteristics are listed in Table 3. Highlighted in green are those that require the mandatory application of photonic technology to achieve specified requirements for the mission. At the same time, other technologies used optoelectronic components for the traditional functions of the spacecraft equipment.

It should be noted that despite the fact that Tables 2 and 3 were compiled at different times, their contents are somewhat correlated. This means that the development of advanced photonic technologies is carried out in a coordinated manner with the experience obtained in the course of the ongoing missions.

The main risks identified during the development of optoelectronic components have been associated with the innovativeness of the research, so the main recommendation for the developers was to advance the development of the critical components to ensure the overall success of a new mission as a whole.

Work [42] shows the results of the efforts of the French Space Agency (CNES) in development of photodetectors operating in different spectral ranges: ultraviolet (UV), visible (VLR), the near (c), middle (MIR) and the far infrared (FIR). Major progress in this direction is achieved by:

– the coordination of the R&D based on the requirements identified by the thematic road maps;
– the existing possibilities of achieving a record performance of the optoelectronic devices that use single-element-cooled infrared detectors, as well as the large-format CCD sensors;
– taking into account the cosmic radiation at ground tests by comparing the results of the flight and ground tests.

All these works are carried out in close cooperation with the developers of the Photonis, LETI/LIR, SOFRADIR, Cypress, e2v technologies, CMOSIS companies.

Work [43] lays out the need for opto-electronic components for space purposes. It is noted that these components have reached the required level of technological readiness in telecommunications and land infrastructure, clearly increasing the use of photonic technologies in the promising methods of telecommunications, which is associated with a number of advantages, including:

– virtually unlimited bandwidth of frequencies;
– lossless;
– low weight;
– small size of the printed circuit boards;
– mechanical flexibility for components such as optical fiber;
– immunity to electromagnetic interference;
– simple electrical isolation.

However, for space applications the readiness of the listed optoelectronic technologies is still very limited, primarily due to problems with the reliability associated with the harsh environments of the outer space. Article [43] analyzed the needs in different types of optoelectronic components used in a wide range of space applications, from signal generation to signal processing on board the spacecraft, signal reception, its processing and routing. It can be argued that the implementation of photonic technologies in space technology is still in its infancy, primarily because a considerable amount of work is required to achieve the readiness level comparable to the terrestrial applications, while ensuring an acceptable level of quality and reliability.

Today, ESA is already using photonic technology for different purposes in a number of space projects, for example, SMOS, GAIA, DARWIN, Herschel, Bepi-Colombo and others. It should be noted that the major space companies are reluctant to proceed with the development of photonic components for space applications mainly because the market for space products is very limited, as compared, for example, to telecommunications.

Another important, but so far not studied enough application of fiber optic technology, is the possibility of modulation of optical signal with the microwave radiation used in radar, communications, electronic warfare systems, as well as in device engineering [44]. This article details the broadband detectors and waveguides for the photonic generation of high-frequency signals, because they are the key components for ensuring the effectiveness of the implementation of fiber optic systems of the millimeter and submillimeter range. The article examines and discusses several technologies, systems, and applications in which the fiber optic technologies provide a competitive advantage against their electronic counterparts, which will significantly expand the field of applications for the microwave frequency range.

Currently, new opportunities are emerging in the field of information and measurement systems for aerospace hardware, including the ability to replace a significant number of sensors of the traditional sensor-transducer devices (STD) with fundamentally new sensors

Table 3. New technologies on board the Pleiades ERS satellites.

	Equipment	Technology	Enhancement
Surveying equipment	Panchromatic detector	Precise CCD receiver with reverse exposure and antich-arge loss structure	More efficient exposure and no image blurring due to the charge loss
	Highly integrated focal plane	Highly integrated FPGA technology	High density of integration
	Lens	Carbon/carbon structure	Low weight, high temperature stability
Image processing and telemetry	Very high speed digital communication	Commercially available 1 Gbit/s	Reduction of mass and energy consumption
	Data compressor	Wavelet transform algo-rithm at a rate of 2 bits/pixel	Minimizing the weight of on-board memory and the input data rate
	Telemetry modulator	Treyllis codes in X-range with the 8 PSK modulation	High-speed low-error data line
Guidance and stabili-zation system	Inertial navigation system	Fiber optic gyroscope	Low noise, high stability
	Gyroscopic torque control	Bearing technology	High connection with high torque, providing high dynamic stability
Power system	1500 W Solar battery	Gallium arsenide triple junction	High efficiency (26%) and a small area
	150 a/h battery	Lithium ion	High specific energy density

Source: data of [41].

based on photonic technologies for measuring electrical and non-electrical parameters with a previously unattained level of precision.

One of the critical components of such devices are analog-to-digital converters (ADCs) used in the development of advanced digital (software controlled) signal receivers and directly convert sensor signals to digital data for subsequent processing. However, the improvement of the ADC modules is progressing slowly due to the large number of problems associated with manufacturing very high resolution (with large number of signal quantization levels) and high conversion speed electronic circuits. The wide bandwidth and high resolution of the ADCs allow all kinds of measurement sensors to produce analog signals directly on the carrier frequencies of radio signals, eliminating the need for lowering the frequency of the analog signal. Currently, such solutions have already been found by means of photonic conversion technologies that implement record characteristics compared with the best electronic ADC. The capabilities of optical and optical-electrical devices make it possible to use 12-14 bit signal quantization at a rate of about 10 gigasamples per second (GS/s) in comparison with the best parameters of electronic ADC, providing only 3 bit conversion at a speed of 8 GS/s.

Work [45] analyzed almost 30 years of experience in the creation of photonic ADCs, simultaneously describing modern electronic ADC to illustrate the principles of their operation, their fundamental properties, as well as the analog optical communication lines used in many photonic ADCs. Thus, 4 classes of photonic ADCs are examined: 1) ADCs with elements of photonic technology, in which photonic devices added to a purely electronic ADC to improve the performance, 2) ADCs with photonic sampling and electronic quantization, 3) ADCs with an electronic sampling circuit and a photonic quantizer, and 4) ADCs with fully photonic sampling and quantization. In conclusion, the possibilities of the future photonic ADCs are discussed. Note that even at the beginning of the second decade of the 21st century, the maximum rate of electronic quantization achieved was 18 GHz, while the optical sampling circuits provided a rate of 100-200 GHz.

The results of the laboratory studies of the photonic ADC for space applications are presented in Work [46]. It is shown that in comparison with a traditional electronic ADC, the photonic ADC has a 200% advantage, especially in energy consumption and weight.

The simulation proved the proposed approach to be very promising, bearing in mind the fact that the sample tested in the laboratory has achieved a performance similar to traditional analog systems with significantly reduced complexity, size, weight and power consumption.

Work [47] covers the effective use of photonic technologies in a number of fiber optic sensors to measure various environmental parameters: temperature, pressure and humidity. These devices are based on different spatial arrangement of the sensor active region. Fluctuations of pressure, temperature, geometric deformations of the hull of a spacecraft affect the properties of the light beam propagating through the optical fiber, its phase, polarization, amplitude or range. The measurement accuracy of such devices, however, is unattainable for conventional DPAs.

In the built-in sensors, the optical signal modulator is used as a component of the optical fiber proper, one or more physical properties of which are subject to external influences and changing. External influences affect the optical fiber, which, in turn, changes some of the characteristics of the light beam within the optical fiber.

Recent advances in the development of the photonic sensor and transducer devices (PSTD) have attracted a stable interest of developers to their use for space applications both the on-board and ground-based.

Initially, the main advantage of the PSTD was their high-speed performance. With the improvement of the PSTD the following advantages are becoming increasingly relevant:

- passivity (the sensors do not require power supply);
- high sensitivity;
- small size and weight;
- high noise resistance;
- ability to operate in harsh environmental conditions (resistance to temperature, mechanical stress, etc.);
- multiplexing of electrical and optical signals.

Since the 2000s, special attention is paid to scientific research and designs based on various properties of magnetic fields and the effects associated with their impact on optical media [48]. Such measuring devices are already used in industrial process control systems, measuring and computing equipment, fault detection, etc. [49]. The Russian Federation has also seen an increasing interest in the development and research of such PSTDs. Developments carried out in Institute of Radio Technologies and Electronics of the Russian Academy of Science, National Research University of Electronic Technology, Moscow State University, Moscow Power Engineering Institute, Moscow State Technical University and others.

The application field for magnetic optical-electronic structures, relevant for the rocket and space industry, is development of the electric current sensors for non-contact measurement and current control in signal and power circuits of electronic equipment, power wires and cable of the devices, etc. These sensors would provide reliable electrical isolation of current carrying circuits of different voltages on the measuring circuits. They also will eliminate the need of discontinuities in the current-carrying circuits to include a measuring device (especially important for high-current lines and cables); they provide resistance to the effects of ionizing radiation of the outer space. The sensors do not require power supply and allow direct interfacing with fiber optic communication lines of the telemetry systems. Creating these current sensors can qualitatively improve the reliability and service life of products the industry backbone enterprises: FSUE “NPC AP”, JSC “Energia”, FSUE “Khurynichev State Research and Production Space Center”, JSC Progress, etc.

Another promising application of the photon technologies close to the practical implementation is creating microcavisies in the “whispering gallery” mode [50]. The range of applications extends from the creation of high-Q resonators for the optical and microwave range [51] to ensure the effective broad area radiation input into single-mode optical fiber [52].

Work [53] reported that a group of young specialists of the Russian Federal Agency of Technical Regulating and Metrology that manufactured and studied the prototype of ultra low-noise microwave oscillator based on the type of resonator disk leucosapphire a "whispering gallery", operating at a frequency of 6.8 GHz. The developed technology enables the production of these resonators in the frequency range of 6.0–10.0 GHz. The studied sample demonstrates a Q-factor as high as 450000 in the microwave frequency range at about -40°C. It is planned to continue studies at lower temperatures to increase the Q-factor of the resonator. It is expected that by 2025 it will be possible to start a mass production of such microcavities with a record Q-factor of about 1000000.

A very important application area of photonic technologies in the creation of space vehicles is the use of fiber optic gyros (FOG). Fundamentals and principles of operation of FOGs and sensors based on fiber optic technology are detailed in a number of papers, such as, [54, 55]. Moreover, according to US experts, in the near future FOGs will replace the widely employed mechanical gyros [56].

The latest research focuses on the development of miniature versions of FOGs for use in small-sized spacecraft, among other applications [57]. It is noted that FOGs have significant advantages compared to other technologies. Thus, in contrast to mechanical gyroscopes, FOGs contain no moving parts, therefore they are more compact, lighter and do not have a counter orientation in space. Compared to the ring laser gyros, FOGs do not require precise adjustments, are better suited for use on the spacecraft, do not require a vibration anti-lock mechanism. Finally, in contrast to the MEMS gyros, FOGs have a better resistance to impact and vibration, and show much better performance. So, the FOGs designed for onboard use (NG LN-200) have better stability (<<1°/hour) and much better noise resistance parameters (<<0.05°/hour). Key technological advantages of FOGs over laser gyros are given in [58], where their common and distinctive characteristics are discussed; some advantages of the FOG technology are presented.

Works [59, 60] provide an overview of the current state of development of fundamentally new materials, called metamaterials, artificial electromagnetic media, the structure of which is scaled in proportion to the wavelength of the radiation propagating in them. They were originally intended for the production of lenses with negative refractive indices. They then became the basis for development of the electromagnetic environment for the controlled wave propagation, which encouraged the revision of the laws of classical geometric optics.

Work [61] considers reflective coatings of silicon carbon. Their main task is to protect the spacecraft from the strong electromagnetic radiation of gas in the shock layer during the re-entry. The structures of silicone carbon and glass carbon that increase the reflected radiation are presented. The numerical simulation and optimization of photonic structures are conducted. Among the materials considered, the resonant structures of layer-by-layer, stacking volume, porous and waveguide type, which evaluated the role of the existing structural defects. It is expected that in future these materials may form the basis of the protective coatings applied in space technology.

Conclusion

The analysis of photonic technologies relevant for space applications demonstrated that photonic technologies can be prioritized both by the levels of technological readiness and demand as follows:

– on-chip photonics: the technologies correspond to the 3-5 TRL levels and have the highest priority for space applications with a relatively short implementation time (about 3 years);

– photonic FOCL and sapphire FOCL used in space device engineering and thermal control, and airgel array packaging of photonic elements used for the thermal protection of spacecraft;

– all technologies with the levels of technological readiness of 3-5 with 3-5 years of implementation;

– interferometers and spectroscopes in early development and requiring fairly long periods of implementation (5-10 years).

Of particular note is the high potential of large-format photosensitive multielement receivers, especially in IR and UV spectral ranges, as well as a variety of metamaterials. The development of such devices is very viable in the medium term (3-5 years).

It is necessary to constantly bear in mind the increased requirements on the reliability and radiation resistance of the components based on photonic technologies, as well as the obligatory flight qualification of such products, to provide a guarantee of their implementation in the target and service SC hardware.

Given the almost completely exhausted potential of the traditional technologies, to support sustainable development and a competitive level of the Russian space technology it is necessary to master modern methods and design tools and develop new technologies, currently not available in the Russian market.

To accomplish this task it is necessary to develop a comprehensive industry target program "Photonics for space", that should include a clear roadmap of creation and implementation of a specific product range of photonic devices, primarily for the space device engineering. After the development of this program is complete, it is advisable to conduct its in-depth discussion at the Scientific Technical Council of the Roscosmos, as a result of which it can be approved for realization by the space industry organizations.

Creating such a program will consolidate the efforts of the industry development, as well as various departments in order to create elemental component base for a new generation of space industry.

The main problem in accelerating the development of this direction in the Russian Federation is associated with a complete lack of inter-departmental coordination. Roadmap of photonics has been in development for several years, but has never formed into a program of mass production. Various agencies are trying to solve problems independently, even realizing that their own efforts are not enough to fully implement the technology.

A coordinated program of development and manufacturing of photonic products should be drafted as the main recommendatory document for the development of photonic technologies for space applications. It should be tightly focused on the creation of the products with a guaranteed demand in various sectors of the Russian economy. Of course, the baseline work must be carried out with the participation of the universities and institutes of the Ministry of Education, as well as development institutions (Skolkovo, Rosnano, etc.). At the same time, the Ministry of Industry of the Russian Federation, Roscosmos and Rosatom will act as customers of those works.

Given the limited funding opportunities offered by the work in the conditions of economic crisis, possible solution could be the adoption of a set of ADC agencies, allowing them to focus limited resources on the breakthrough development projects.

Finally, it is extremely important to organize the international cooperation, i.e. with the BRICS countries.

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