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A scientific session of the General Meeting of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the conference hall of the Lebedev Physical Institute, RAS on 17 December 2012.

The following reports were put on the session's agenda posted on the website www.gpad.ac.ru of the RAS Physical Sciences Division:

(1) **Dianov E M** (Fiber Optics Research Center, RAS, Moscow) "On the threshold of a peta era";

(2) **Zabrodskii A G** (Ioffe Physical Technical Institute, RAS, St. Petersburg) "Scientists' contribution to the Great Victory in WWII on the example of the Leningrad (now A F Ioffe) Physical Technical Institute";

(3) **Ilkaev R I** (Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics, Sarov) "Major stages of the Soviet Atomic Project";

(4) **Cherepashchuk A M** (Sternberg State Astronomical Institute of Lomonosov Moscow State University, Moscow) "History of the Astronomy history".

Papers written on the basis of the reports are published below.

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On the Threshold of Peta-era

E M Dianov

1. Introduction

The history of the progress of human society is also the history of advancement of means of communication and information transfer. While at the early stages of the development of human society use was made of simple means like smoke signals, messengers, and post, the development of society resulted in perfecting the means of communication. The rapid advancement of science and technology in the 19th century resulted in more efficient means of communication, but the demand for information exchange always exceeded technical capabilities. That is why the achievements in science and technology were employed first of all to develop the means of communication. We shall give examples of the most impressive technical achievements in the history of the creation of the means of communication.

In 1794, the Chappe brothers built the first optical telegraph between Paris and Lille (225 km), which consisted of a chain of towers located within line of sight distance from each other. Messages were visually transferred from tower to tower by semaphore alphabet. The world's longest optical telegraph line operated between Petersburg and Warsaw (1200 km) and it took 15 minutes to transmit signals.

In 1837, an American artist and entrepreneur Samuel Morse invented an electromagnetic telegraph set and a dot-and-dash code. The first commercial telegraph line was built between Washington and Baltimore in 1844. The discovery of gutta-percha was employed for the insulation of electric wires, which permitted laying an underwater telegraph line between England and France across the English Channel in 1851.

In 1857, a start was made on laying the telegraph cable between Europe and America on the bottom of the Atlantic Ocean. This first attempt to lay a cable on the ocean bottom encountered great technical difficulties which were overcome only after several attempts. This event of world significance was vividly described by Stefan Zweig in his novella "Das erste Wort über den Ozean (The first word across the ocean)". The world's longest telegraph line, Moscow–Vladivostok, which measured about 12 thousand kilometers, was opened in 1871.

In 1876, Alexander Graham Bell invented the telephone, and in 1880 48,000 telephone sets were already in use in the USA. In 1880, Bell invented the optical telephone (Bell's photophone) and implemented the transmission of voice signals over a distance of 200 m via free atmosphere, with sunlight being employed as the carrier radiation.

Hertz's 1888 discovery of electromagnetic waves and the making of a spark transmitter of radio waves laid the foundation for the emergence of radio communication. Alexandre Popov in 1895 and Guglielmo Marconi in 1896 demonstrated the possibility of transferring signals by radio waves. In 1901, Marconi realized radio-telegraphic transmission across the Atlantic Ocean. In 1909, G Marconi and Karl F Braun shared the Nobel Prize in physics "in recognition of their contributions to the development of wireless telegraphy".

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The 20th century saw a rapid development of radio communications. Satellite radio communication appeared in 1965. For experts, it was clear that the information transfer rate is proportional to the carrier radiation frequency, when the transfer is effected by carrier radiation. That is why the development of radio communications followed the path of shortening the carrier radiation wavelength (of increasing frequency), making it possible to transfer progressively greater information volumes. Despite the high level of radio communication development in advanced countries, including the Soviet Union, the growing demand for information by developed countries led to the realization of the necessity to move to optical radiation, which showed promise of increasing the information transfer rate by a factor of 10^4-10^5 over that in radio communications. The present state of optical fiber communication amply bears out these expectations.

To conclude this section concerned with the history of the advancement of means of communication, I would like to emphasize that Russia and the Soviet Union were among the leaders in their progress.

In what follows, first I will briefly dwell on the landmarks in the history and present-day state of optical fiber communication. Next, I will address the mechanisms which limit the rate of information transfer along an optical fiber in modern optical fiber communication lines, discuss different ways of overcoming these limitations, and present recent findings of the corresponding research as well as predictions for the development of optical fiber communication for the next ten years.

2. History of the development of optical fiber communications

There is a good reason to review the history of the development of optical fiber communication beginning with Bell's experiments on the transmission of voice signals through free atmosphere with the aid of sunlight (Bell's photophone), as mentioned in the Introduction. These experiments also revealed the main difficulties of applying optical radiation for information transfer, which were overcome to allow making efficient optical fiber communication systems. Using the photophone scheme presented in Fig. 1, Bell managed to transmit a voice signal over a distance of 200 m. Despite the success of these experiments, Bell failed to advance this success — and it is clear why: the Sun is not a suitable light source for information transfer and the free atmosphere is not an advantageous transmission medium. Other, more suitable light sources and transmission media were nonexistent at that time. Thus, no serious attempts to harness optical radiation for information transfer were undertaken during the next 80 years, until the appearance of the first lasers.

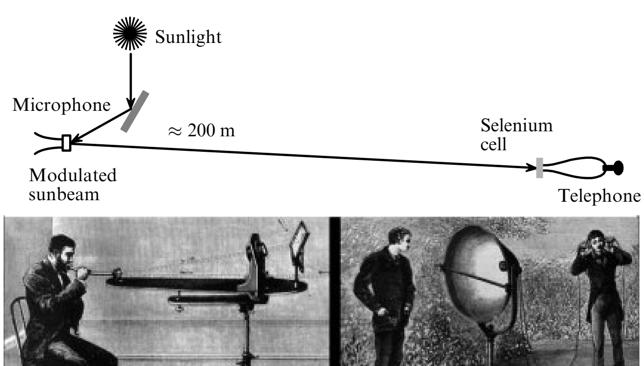

Figure 1. Bell's photophone.

The creation of lasers and their extensive development led to the emergence of several new fields of science and technology, including modern fiber optics and optical communication. The decisive role in the advent of lasers was played by American and Soviet scientists. In 1964, the Nobel Prize in physics was awarded to N G Basov, A M Prokhorov, and C H Townes "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle".

Lasers were a perfect light source for information transfer, providing low-divergent high-power radiation. The monochromaticity of laser radiation permitted using the ideas and techniques employed in radio communication for information transmission. Therefore, among the first experiments performed with lasers were those on information transfer through the free atmosphere.

The experiments were carried out in several countries (including the USSR), but the result was always the same: the free atmosphere, primarily owing to the variability of its meteorological conditions, is not a suitable transmission medium for reliable information transfer over long distances. There was no other transmission medium at that time: glass optical fibers, which exhibited a high optical loss on the order of 1000 dB km^{-1} (the light was attenuated twofold over a distance of 1 m), could not be used for information transfer over any substantial distance. And it seemed that the brilliant idea of developing high-speed optical communication systems, which were in great demand by modern society, could not be realized. However, as is often the case in history, when society is facing a very important but intractable problem, there will always be a person (or several men) to find the solution to the problem. In this case, the man was Charles Kuen Kao, a Chinese who was working in England at Standard Telecommunications Laboratories Ltd. (Fig. 2). In 1966, he published a paper [1], in which he analyzed the mechanisms of optical loss in glass and showed that this loss was primarily caused by the presence of impurities, first and foremost of transition metals: Fe, Cu, Ni, etc. By purifying glass from these impurities, it is possible to obtain loss figures of less than 20 dB km^{-1}, this figure being much higher than the optical loss bound caused by basic mechanisms.

Based on theoretical and experimental investigations, Kao drew a conclusion that a fiber structure with a core diameter of about the wavelength λ_0 and a total diameter of $\sim 100\,\lambda_0$ can be an optical waveguide suitable for use as a transmission medium for communication systems. According to Kao's estimates, when the difference in the refractive indices of the core and the cladding amounts to about 1%, this waveguide is a single-mode one and is capable of transmitting information with a rate of more than 1 Gbit s^{-1}. Then Kao emphasized that successful implementation of such optical waveguide depends on the availability of a suitable dielectric material with a low optical loss, the development of this material being a difficult but not impossible task.

C Kao's ideas expressed in 1966 were implemented in 1970, when Corning Glass Works fabricated for the first time

Figure 2. C Kao making optical measurements.

glass optical fibers with an optical loss of 17 dB km^{-1} at a wavelength $\lambda = 0.63$ μm.

In 2009, C K Kao was awarded the Nobel Prize in physics "for groundbreaking achievements concerning the transmission of light in fibers for optical communication".

Lowering the optical loss of optical fibers from ~ 1000 dB km^{-1} to ~ 20 dB km^{-1} seemed to be an extremely difficult task. However, Corning Glass Works developed the technological basis for the solution of this problem back in the 1930s [2]. Frank Hyde, a researcher at Corning, carried out investigations aimed at obtaining the pure powder of fused silica in the passage of silicon tetrachloride ($SiCl_4$) vapor through the flame of an oxyhydrogen burner (US Patent, 1934). More recently, they synthesized titanium-doped quartz glass using silicon and titanium tetrachlorides as the raw materials. This glass possessed a close-to-zero thermal expansion coefficient. An advantage of using silicon and titanium tetrachlorides is a possibility of deep purification of these volatile compounds. In the 1950s, demand arose for large plates of pure fused silica for a number of applications, including the fabrication of large mirrors ($\geqslant 1.5$ m in diameter) for new-generation high-precision astronomical telescopes. Therefore, Corning possessed both the fabrication technology and the samples of high-purity fused silica by the beginning of the work to make glass optical fiber with a low optical loss in 1967. However, the first attempts to produce glass optical fiber with a low optical loss using the rod-in-tube method were not successful because of the high optical loss introduced by light scattering at the rod–tube interface. Only the deposition of titanium-doped fused silica powder onto the inner surface of a fused silica tube with the subsequent melting of the porous layer, tube contraction to a continuous rod (a preform), and the drawing of an optical fiber from it led to success: optical fibers with an optical loss of 17 dB km^{-1} at a wavelength of 0.63 μm were produced in 1970. In 1972, it was possible to fabricate optical fibers with a germanium-doped fused silica core with an optical loss of 4 dB km^{-1}. The heroes of this outstanding achievement in optics were Corning staff members Robert Maurer, Donald Keck, and Peter Schultz (Fig. 3).

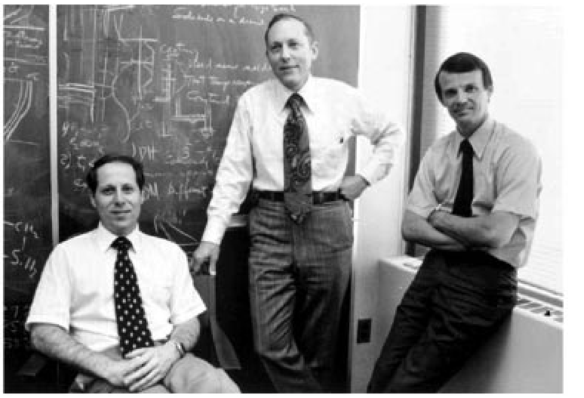

Figure 3. From left to right: Donald Keck, Robert Maurer, and Peter Schultz.

Also in 1970, cw operation of a semiconductor laser based on a GaAlAs double heterostructure was obtained at room temperature in the USSR (Zh I Alferov's laboratory) and in the USA. In 2000, Zh I Alferov and H Krömer were awarded the Nobel Prize in physics "for developing semiconductor heterostructures used in high-speed- and opto-electronics". These two achievements provided the reliable basis for the successful development of optical fiber communication and triggered intensive basic research in many countries, including the USSR, in the technology of optical fibers and their properties, improvement of requisite components, and development of optical fiber communication systems.

As for the basic investigations into quartz glass optical fibers, most attention was given to the optical fiber characteristics important for practical applications in communication systems: optical loss, dispersion, and mechanical strength. Of great interest was the research of nonlinear optical phenomena in optical fibers, which could appear in transmitting optical data through the latter and play a negative role in the process. We mention only the most important results of these investigations, which are well known and have been published in numerous review articles and books on fiber optics (see, for instance, the collection of review papers on different applications of fiber optics in Ref. [3]).

The minimal optical loss of quartz glass optical fibers was found to correspond to the long-wavelength part of the near-infrared (IR) spectral region (to wavelengths $\lambda > 1$ μm). In this case, the optical loss below 0.35 dB km^{-1} corresponds to the $\lambda = 1.3 - 1.7$ μm spectral range, while the absolute minimum of less than 0.2 dB km^{-1} is reached at a wavelength about $\lambda = 1.5$ μm (Fig. 4). It was also discovered that the material dispersion of fused silica is close to zero at $\lambda \approx 1.31$ μm. Investigations of the mechanisms of mechanical strength degradation of optical fibers and technology improvement enabled obtaining long optical fibers (of about 10 km in length) with a tensile strength of about 5 GPa (for optical fibers 125 μm in diameter). Bogatyrev et al. [5] were the first to demonstrate that a hermetic metal coating of optical fibers permits raising the tensile strength by a factor of two.

Extensive basic research of nonlinear optical phenomena in optical fibers showed that, despite the low nonlinearity of fused silica, what is observed in optical fibers is not only virtually all known nonlinear effects in solids, but also several new ones. This is explained by a large length of an optical fiber with a low optical loss (i.e., by the large interaction length) and a small lateral size of the optical fiber core (i.e., by the

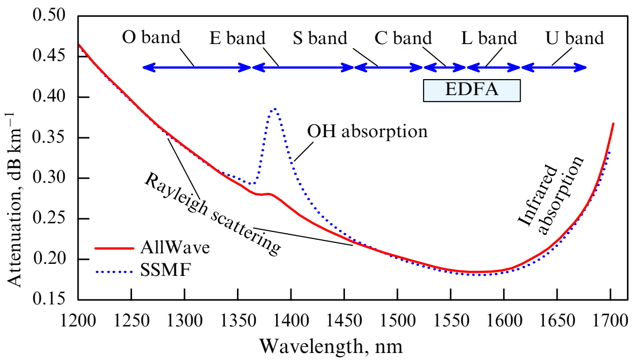

Figure 4. Optical loss spectrum of optical fibers [4]. O, E, S, C, L, and U are spectral band designations employed in the literature. EDFA is the erbium-doped fiber amplifier band. AllWave and SSMF (standard single mode fiber) are optical fiber types.

high radiation intensity), which sharply lowers the thresholds for the emergence of nonlinear phenomena. Nonlinear effects in optical fibers can play a negative role in optical fiber communication systems. In particular, the nonlinear phenomena responsible for the conversion of fundamental wavelength radiation to radiation with other wavelengths may give rise to crosstalk in systems with wavelength division multiplexing. Nonetheless, it has been shown that nonlinear effects may find useful applications in communication systems. For instance, signal amplification by stimulated Raman scattering (SRS) may be efficiently employed to compensate for the radiation loss in communication systems. In this case, the information-transmitting optical fiber simultaneously serves as an amplifying medium with a broad amplification band.

It is pertinent to note here that A M Prokhorov initiated work on the fabrication of low-loss fused silica optical fibers in the Soviet Union in 1973. For raw compounds, use was made of high-purity volatile compounds of silicon, germanium, and boron, which had been elaborated earlier under G G Devyatykh's supervision.

Even early in 1975, optical fiber samples with a low optical loss were fabricated [6] and a start was made on the fundamental study of these optical fibers. Soviet scientists made a significant contribution to the results of the fundamental studies mentioned above. These results obtained in 1975–1985 were reviewed in Ref. [7]. A comprehensive review of nonlinear effects in optical fibers is given in Refs [8, 9].

The results of basic investigations of optical fibers showed the promise of using the 1.0–1.6-μm spectral region for information transfer (see, e.g., Ref. [10]) and initiated the development of several generations of optical fiber communication systems and their requisite components.

Let us mention only the most important results of these research efforts. In 1980, the first commercial optical fiber communication systems with a modest information transfer rate of 45 Mbit s^{-1} at a wavelength $\lambda = 0.85$ μm were put into operation. The choice of carrier radiation wavelength was determined by the availability of the corresponding semiconductor lasers and silicon photodetectors. For a transmitting medium these systems employed multimode optical fibers, whose intermode dispersion limited the information transfer rate.

For information transfer in next-generation optical fiber communication systems, it was planned to employ the spectral region near $\lambda = 1.3$ μm, where the material dispersion of fused silica is close to zero. This provided the possibility of transferring large information fluxes through a single-mode optical fiber devoid of intermode dispersion.

And so, considerable effort went into the development of requisite components (first of all single-mode optical fibers, semiconductor lasers, and photodetectors) and the creation of optical fiber communication systems operating in this spectral range. Mention should be made here of the first studies by Japanese and Soviet researchers on the development of laboratory optical fiber communication systems operating at a wavelength $\lambda \approx 1.3$ μm [11, 12]. In 1988, the first optical fiber communication line was laid on the bottom of the Atlantic Ocean, which connected Europe and America. The system permitted transferring information along a single-mode optical fiber at a rate of 280 Mbit s^{-1} at a wavelength $\lambda = 1.31$ μm and employed OEO regenerators with the conversion of optical signals to electric ones and back to optical signals. The utilization of OEO regenerators limited the information transfer rate, and this brought up the problem of creating a fiber-optic signal amplifier. Intensive research in this area led to the development of two promising fiber-optic amplifiers: an erbium-doped fiber amplifier (EDFA) [13] and an SRS fiber amplifier [14, 15]. The advantage of erbium-doped fiber amplifiers consisted in their high efficiency and the coincidence of the spectral amplification band with the spectral field of low optical loss in optical fibers (see Fig. 4). This led to the development of new-generation optical fiber communication systems operating at a wavelength of about 1.5 μm and using EDFA-based optical signal repeaters. A disadvantage of the erbium fiber amplifier is its narrow amplification band, 80 nm at most (1530–1610 nm), which limits the information transfer rate of modern fiber-optic systems.

The advantage of the SRS fiber amplifier consists in the possibility of obtaining a significantly broader amplification band at any wavelength. The drawback of the amplifier resides in its low efficiency. Despite this circumstance, SRS fiber amplifiers are employed in commercial optical fiber communication systems.

The next impressive achievement in the development of high-speed fiber-optic systems was the use of wavelength-division multiplexing, which enabled raising the rate of information transfer along an optical fiber to the terabit level [16]. Soviet scientists made a substantial contribution at the initial stage of the development of the wavelength-division multiplexing technique (see, for instance, review Ref. [17] and references cited therein).

In concluding this section concerned with a brief history of the advancement of optical fiber communication systems — from the first commercial systems with an information transfer rate of 45 Mbit s^{-1} to terabit systems — I would like to emphasize the extremely important role of the parameters of the transmission medium (of the optical fiber) in this progress. An optical fiber with specific parameters (multimode, multimode with a gradient profile of the refractive index, single-mode with a zero material dispersion, single-mode with the lowest optical loss and the possibility of optical signal amplification, etc.) corresponded to each stage of the technology evolution.

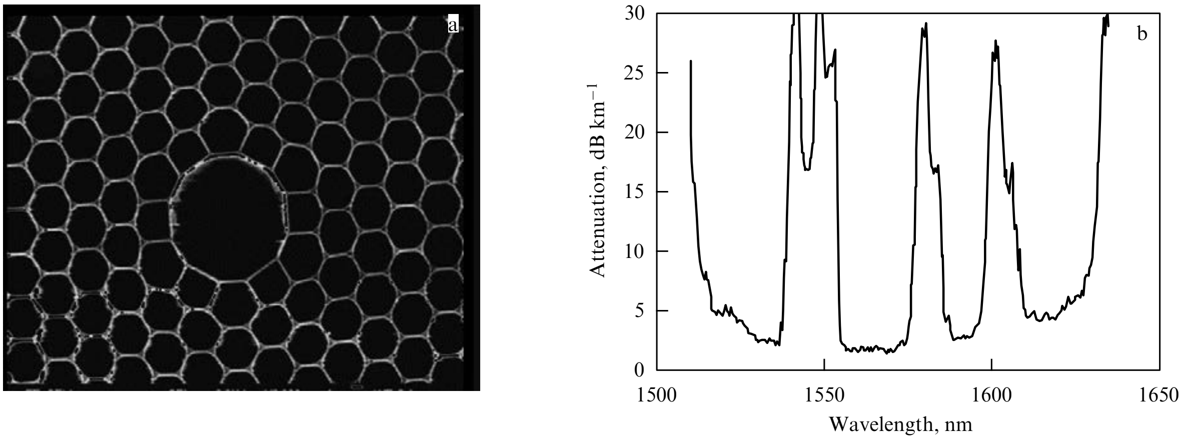

Figure 5. (a) Transverse section of an optical fiber with an air core. (b) Optical loss spectrum of this optical fiber [19].

3. State-of-the-art and prospects for the further growth of data transmission rate over an optical fiber

At present, information may be transmitted in commercial optical fiber systems at a rate of up to 10 Tbit s^{-1}, and in experimental ones with a rate on the order of 100 Tbit s^{-1}. By 2010, the total length of optical fibers laid in communication systems amounted to 1 bln km; according to estimates, this figure will double by 2015. The predicted number of Internet users will range up to 5 bln in 2015.

The demand in developed countries for information rises by 30–40% annually. This signifies that it will be required to transfer information over an optical fiber at a rate on the order of 100 Pbit s^{-1} within 20 years, provided that this demand growth persists. On the strength of several limitations, there is no way of transferring data at this rate over single-mode optical fibers.

In data transfer at a high rate, in other words, over a broad spectral band for long distances, several parameters of the transmission medium, like dispersion, nonlinearity, and optical loss, are critical. In experiments of the 1960s on information transfer through the free atmosphere using laser radiation, it was found that the free atmosphere is not a proper transmission medium, primarily due to the spatial and temporal instability of its parameters, such as the optical loss and the atmosphere density. Glass optical fibers are an ideal transmission medium up to certain, sufficiently high, data transfer rates on the order of 100 Tbit s^{-1}. However, a further increase in the data transfer rate is limited under the effects of nonlinearity, dispersion, and optical loss of optical fibers. At the same time, these parameters of atmospheric air as such are at least an order of magnitude lower than in glass optical fibers. But atmospheric air should not be free, so that its parameters remain stable. Therefore, an idea was conceived to make optical fibers with an air core isolated from external action. In this case, the glass cladding in the form of a photonic crystal provides the mechanism of light propagation along the air core. Suchlike optical fibers were fabricated and their characteristics were comprehensively studied (see, for instance, Ref. [18] and references cited therein). Figure 5 displays the structure of such an optical fiber with an air core and the optical loss spectrum. At present, the minimal optical loss is equal to 1.2 dB km^{-1}, which far exceeds the minimal optical loss in glass optical fibers (< 0.2 dB km^{-1} at a wavelength of 1.5 μm). The relatively high optical loss in optical fibers with an air core is attributable to light scattering by glass roughness arising from frozen surface capillary waves [18].

The solution to the problem of lowering the optical loss in these optical fibers requires further basic research; as of now, experts and scientists are searching for other ways of raising the rate of a data transfer along optical fibers.

Currently, several ways have been explored for overcoming the stated limitations of optical fiber systems with wavelength division multiplexing, which presently afford the highest data transfer rate (Fig. 6). About 100 independent channels with different carrier radiation wavelengths, all of which lie within the amplification band of the optical amplifiers, propagate along the single-mode optical fibers in such systems.

The total data transfer rate equals $B = nb$, where b is the data transfer rate of one spectral channel, and n is the number of spectral channels. When the data transfer rate of one spectral channel is equal to 10 Gbit s^{-1} and the number of channels $n = 100$, the total data transfer rate along one optical fiber amounts to 1 Tbit s^{-1}. One way to raise the data transfer rate involves increasing the number of spectral channels; to do this requires broadening the spectral region for information transfer. As is evident from Fig. 4, the spectral region in which the optical loss is below 0.35 dB km^{-1} measures 400 nm (1300–1700 nm), but optical amplifiers are nonexistent for this spectral region. Therefore, the development of optical fiber amplifiers for this spectral region is a high-priority task.

In 2005, the Fiber Optics Research Center of the RAS in collaboration with the G G Devyatykh Institute of Chemistry

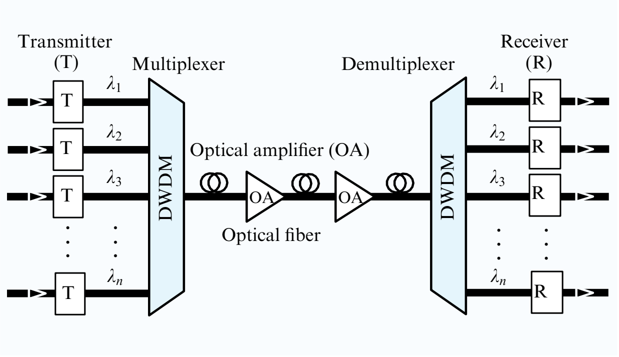

Figure 6. Dense wavelength division multiplexing (DWDM) schematic.

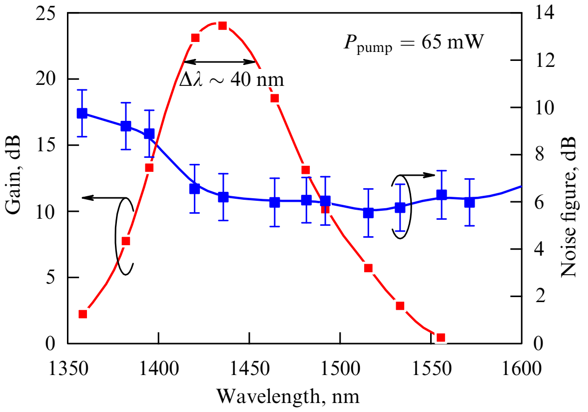

Figure 7. Gain spectrum of a bismuth fiber amplifier.

of High-Purity Substances of the RAS were the first in the world to develop the fabrication technology of bismuth-doped optical fibers, whose luminescence spectrum covers the specified spectral region [20]. Demonstrated for the first time in the same year was a bismuth fiber laser with cw lasing in the 1150–1300-nm spectral region [21]; more recently, a family of bismuth fiber lasers was made, which lased in the 1150–1550-nm spectral region [22]. The employment of a bismuth-doped optical fiber — a new promising active medium [23, 24] — permitted making the first step in the creation of efficient fiber amplifiers for the 1300–1500-nm spectral range. For the first time, it has been possible to develop a bismuth fiber amplifier for the 1425–1465-nm spectral region; the amplifier, pumped by a 65-mW laser diode at a wavelength of 1310 nm, exhibited a maximum gain of 25 dB (Fig. 7) [25].

Another way of increasing the rate of information transfer over an optical fiber is to raise the information transfer rate b in a spectral channel. According to the presently accepted standards, $b = 40$ Gbit s^{-1}; however, a figure $b = 100$ Gbit s^{-1} has already been obtained experimentally due to the multilevel modulation of the carrier radiation [26], and intensive research is underway to make so-called superchannels with figures $b = 400$ Gbit s^{-1} and higher.

Yet another way of raising the data transfer rate, which has attracted considerable recent attention, is spatial channel multiplexing by making multicore optical fibers and a few-mode optical fiber in which each mode is the carrier of independent channels.

Outlined below are new results reported to the 38th European Conference on Optical Communication (2012), which bear on the development of superchannels, multicore and few-mode optical fibers, and the corresponding optical fiber amplifiers. Also given are the most interesting results on information transfer with spatial channel multiplexing.

Chien et al. [27] and Liu et al. [28] reported the generation of superchannels with a data transfer rate of 512 Gbit s^{-1} and 1.5 Tbit s^{-1}, as well as the passing of these channels through distances of 2400 km and 56 × 100 km, respectively. Gnauck et al. [29] implemented the transmission of eight superchannels (at a rate of 603 Gbit s^{-1}) along each core of a seven-core optical fiber through a distance of more than 845 km.

A number of multicore optical fibers have been developed and investigated to date, including 7-core, 12-core, and 19-core ones.

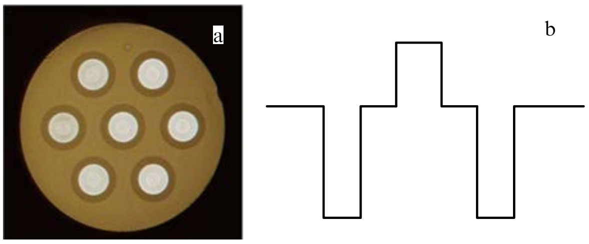

Figure 8. (a) Typical structure of a 7-core optical fiber. (b) Profile of the refractive index of a core in a multicore optical fiber.

The technical requirements imposed on multicore optical fibers are that the optical loss should be low in all cores, the crosstalk between the neighboring cores should be low, and their diameters should not be too large (cladding diameter $\leqslant 200$ μm). Figure 8a demonstrates a typical structure of a 7-core optical fiber. The strength of crosstalk depends on the separation between the neighboring cores. Furthermore, by selecting a special profile of the refractive index (for instance, as in Fig. 8b), it is possible to substantially weaken the overlap of the optical fields in the neighboring cores, which naturally lowers the crosstalk. Imamura et al. [30] described a 7-core optical fiber with a cladding diameter of 186 μm and a spacing of 55 μm between the neighboring cores. The refractive index profile of the core is similar to that depicted in Fig. 8b. The measured crosstalk between the neighboring cores in this optical fiber amounts to -40 dB upon transmission over a distance of 100 km.

The development of a transmission medium in the form of a multicore optical fiber for data transfer over long distances ($\geqslant 100$ km) calls, in turn, for the development of multicore optical fiber amplifiers. Tsuchida et al. [31] presented the parameters of a 7-core erbium fiber amplifier developed in their work. The optical fiber diameter is equal to 180 μm, the spacing between the erbium-doped cores is equal to 45 μm, and the optical fiber is 16 m long. For a pump power of 40 mW, they obtained a gain of over 15 dB, a noise figure under 7 dB, and crosstalk below -40 dB.

Takahashi et al. [32] presented the results of the first demonstration of signal transmission with spatial channel multiplexing (7-core optical fiber) and a 7-core erbium amplifier through a distance of 6160 km at a data transfer rate of 35.8 Tbit s^{-1}. In this case, 40 spectral channels each with a data transfer rate of 128 Gbit s^{-1} were introduced into every core of the 7-core optical fiber.

Of considerable interest is the development of a six-mode erbium fiber amplifier, described by Salsi et al. [33]. The difficulty of making such an amplifier consists in ensuring equal amplification of the signals transferred by different modes. The paper describes an amplifier with six modes: LP_{01}, LP_{11} (two degenerate modes), LP_{21} (two degenerate modes), and LP_{02} which have different power distribution over the section of the optical fiber. To obtain equal amplification of the signals transferred by the different modes requires the corresponding pump power distribution over the section of the active optical fiber . So far, the authors have not managed to solve this problem: the difference between the signal gains for the different modes amounts to 3–4 dB.

Sleiffer et al. [34] implemented data transmission through a distance of 119 km at a rate of 73.7 Tbit s^{-1} using a three-mode optical fiber and a three-mode erbium optical amplifier.

In this case, 96 spectral channels each with an information transfer rate of 256 Gbit s^{-1} were introduced into each mode.

Finally, the most remarkable result reported by Takara et al. [35] to this conference was data transmission along a twelve-core optical fiber at a rate of 1.01 Pbit s^{-1} over a distance of 52 km. In this experiment, 222 spectral channels each with an information transfer rate of 456 Gbit s^{-1} were introduced into each of the 12 cores. The carrier radiation of the 222 spectral channels occupied the spectral regions C and L (1526.44–1565.09 nm and 1567.95–1620.06 nm); in this case, the carrier radiation frequencies of the neighboring channels were spaced at 50 GHz.

The reports presented to the conference show the promise of using spatial channel multiplexing to raise the information capacity of optical fibers to the petabit level.

Unfortunately, Russia cannot praise itself for similar findings. Despite a high level of basic research in the area of fiber optics at institutes of the Russian Academy of Sciences, the development of modern fiber-optic means of communication and information transfer is not among the priority tasks of the Russian State.

4. Conclusions

Two outstanding breakthroughs in optics — the creation of lasers and the development of glass optical fibers with extremely low optical loss — provided a great breakthrough in the development of the means of communication and data transfer — the development of previously unattainable high-speed (terabit) optical fiber systems.

The level of the development of a modern society is determined by the possibility of using unrestrictedly large information fluxes, and this is nowadays reflected in the annual 30–40% growth in the demand for information in developed countries. Modern terabit optical fiber communication and data transfer networks have turned into a peculiar kind of a nervous system of a developed society, which, by analogy with a human nervous system, controls the functioning of all State organs.

The above-mentioned growth in the demand for information gives evidence that within the next 5–10 years optical fiber communication systems with a data transfer rate of 1–10 Pbit s^{-1} along a single optical fiber will become a necessity.

The results of the corresponding recent research, which are outlined in this paper, demonstrate the feasibility of solving this problem.

The development of petabit data transfer systems and the making of petaflop supercomputers signify that humanity is on the threshold of peta-era in the area of information processing and transfer.

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