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On the threshold of Tera era

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Abstract. A brief review is presented of the state of the art of fibre optic communication based on materials of the conferences held in 1999. The main attention is paid to fibre optic systems with the spectral multiplexing of channels and the bit rate of $\sim$ 1 Tbit s^{-1}.

1. Introduction

The world is entering the third millennium. And although there are doubts and arguments on when a new millennium begins, in 2000 or 2001, there is no any doubt that the world is simultaneously entering the information era, or Tera era. The latter name reflects the rates of data transfer and processing equal to 10^{12} bit s^{-1} (terabit s^{-1}) and 10^{12} operation s^{-1}, respectively, which will be achieved in the near future.

The information era is characterised, on the one hand, by a continuously increasing necessity of the mankind in the information exchange, and on the other, by the technical possibilities of satisfying this necessity in virtually full measure. The history of the development of means of communication and data transfer is an inherent part of the mankind history, a necessity in the information exchange always exceeding the technical possibilities available. Any society takes care of means of communication and makes large investments in their development by using the newest advances in science and technology (of course, next to the military expenditures). And only now, on the threshold of a new millennium, the mankind is ready to provide technical conditions for a virtually complete fulfilment of its necessity in the information exchange by using optical methods for data transfer, processing, and storage.

In this paper, I will consider only the current advances in the field of fibre optic communication and data transfer systems, which represent a most important element of the information technology. Fig. 1 shows the dynamics of development of communication systems for the last 100 years. One can see that for 90 years of the development of communication technology, the capacity (the data rate) of communication lines has increased by five orders of magnitude, beginning from the first telephone lines that had the bit rate of the order of 1 bit s^{-1}. For the last 20 years, the bit rate of communication lines has increased approximately by the same five orders of magnitude and has achieved $\sim$ 1 Tbit s^{-1}.

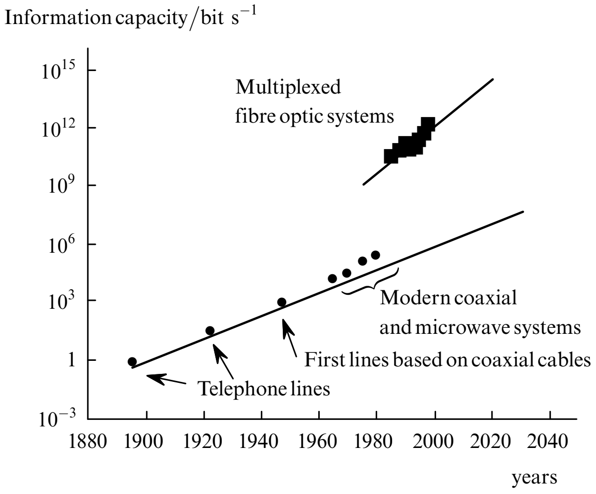

Figure 1. A change in the relative capacity of communication systems for the last 100 years.

The scale of the development of fibre optic communication is indeed amazing. At present, the world's production of optical fibres amounts to 60 millions km per year. For each minute, more than 100 km of fibre optic communication lines are being laid in the world. All the continents are interconnected with submarine fibre optic cables, whose total length is sufficient to encircle the earth six times. The development of broadband optical amplifiers resulted in the creation, at the end of 1990s, of fibre optic communication systems with the spectral multiplexing of one hundred and more channels, which provided the total bit rate of more than 1 Tbit s^{-1} [1].

The principle of operation of wavelength-division multiplexed (WDM) systems is explained in Fig. 2. Emission at different wavelengths (at present, as a rule, from independent light sources), each of them carrying its own information, is coupled into an optical fibre using a special device (a multiplexer), amplified by an optical amplifier, and propagates over a fibre communication line. At the output of the communication line, after the optical amplifier, a demultiplexer decomposes the emission over the wavelengths.

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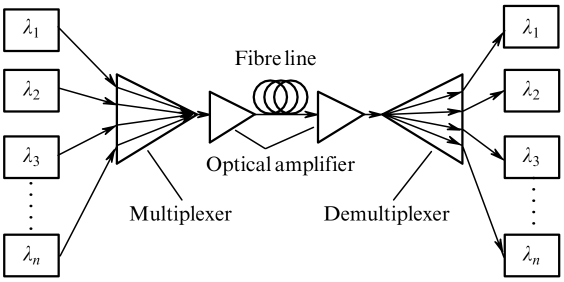


Figure 2. Principal schematic of the multiplexed fibre optic communication system.

Terabit WDM rates in multiplexed systems impose certain requirements on their elements; first of all, on light sources, optical amplifiers, and optical fibres. Before discussing these elements, consider briefly some parameters of such systems as a whole.

The total data transfer rate B is determined by the expression

$$B = Nb,$$

where N is the number of spectral channels; b is the transfer rate over one channel, which at present is 2.5 – 40 Gbit c^{-1}. Successful works are underway on increasing the transfer rate over a channel up to 160 Gbit s^{-1} by using the optical time data multiplexing. The number N of spectral channels achieves 100 and more.

The amplification band of modern optical amplifiers, which has a width of 30 – 80 nm, is one of the main factors that restrict the number of spectral channels and the total data transfer rate. An important characteristic of the multiplexed systems is the difference between the wavelengths (frequencies) of adjacent channels. At present, it lies, as a rule, in the range from 0.2 to 0.75 nm, or from 25 to 100 Hz.

Let us now turn to light sources, optical amplifiers, and optical fibres, which are used at present, and discuss briefly the prospects of the development of these important elements.

2. Light sources

Distributed feedback diode lasers are most widely used today. A fundamental drawback of these lasers is the dependence of their emission wavelength on the temperature variations. Because the wavelength difference of the adjacent spectral channels is fractions of nanometers, diode lasers should be thermally stabilised, which increases the cost of the system. The wavelength of a light source should be controlled within an accuracy of 0.05 nm.

Fibre lasers, in particular, erbium lasers emitting between 1.53 and 1.62 μm are devoid of this drawback. These lasers are pumped by laser diodes and represent efficient and stable light sources for multiplexed systems (see, for example, [2, 3]). Another promising light source is a supercontinuum generated in optical fibres using a number of nonlinear effects upon excitation by sufficiently powerful femtosecond pulses. Thus, this method was used in Ref. [4] to obtain a stable light source in the spectral range from 1.45 to 1.65 μm with a spectral width of 200 nm. The required number of light sources with the specified differences between their wavelengths can be obtained using optical filters.

3. Optical amplifiers

Three types of optical amplifiers are used today in fibre optic communications systems: semiconductor optical amplifiers, erbium fibre amplifiers (EFA), and Raman (SRS) fibre amplifiers. Because of the fast amplification dynamics of semiconductor optical amplifiers resulting in a crosstalk between different spectral channels, these amplifiers have not been used in multiplexed systems so far. Erbium fibre amplifiers, whose full spectral amplification band has a width of about 80 nm (the C and L amplification bands) (see, for example, Ref. [5]), are used today most often.

Another important characteristic (except the amplification band width) is a flatness of the amplification spectrum. The amplification spectrum should be flat because all the spectral channels should have the same amplification. Because, as a rule, neither of the amplifiers have a flat amplification band, the amplification spectrum is flattened using optical filters of different types.

Raman amplifiers are promising for applications in fibre optic communication systems because they offer a number of the following fundamental advantages (see, for example, Ref. [6]):

(i) They can amplify light at any wavelength;

(ii) an optical fibre itself can be used as an active medium;

(iii) their amplification spectrum depends on the pump spectrum, so that, in principle, a very broad (over 100 nm) amplification band can be obtained by a proper choice of pump sources; and

(iv) they have low noise.

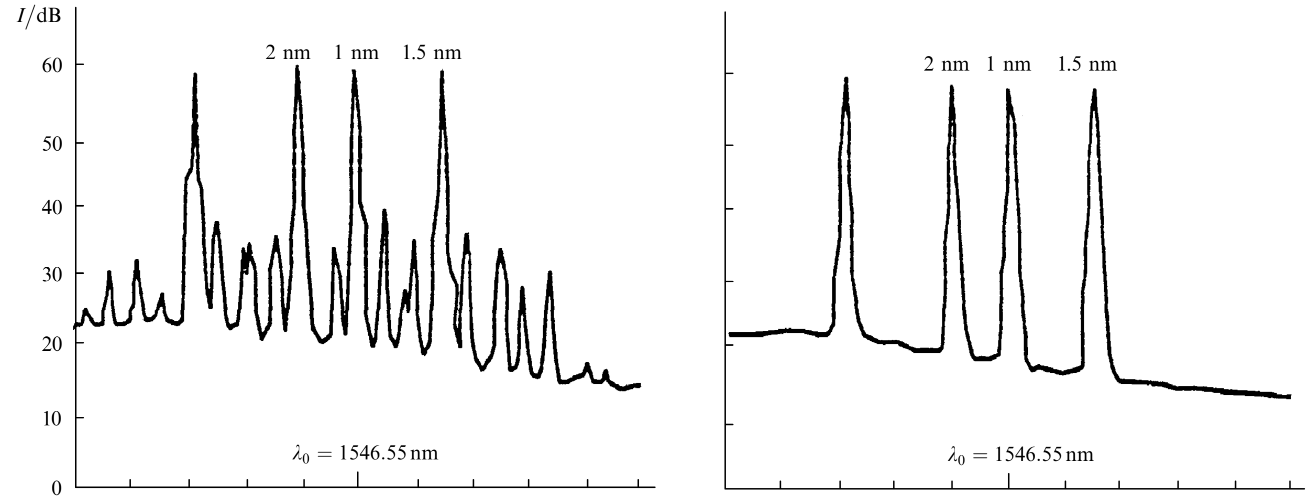
The main disadvantage of Raman amplifiers is their low efficiency, which requires the use of quite powerful ($\sim$ 1 W) cw pumping to obtain the gain of about 30 dB (a typical value for optical communication systems). Until recently, such pump sources were not available in the wavelength range from 1.2 to 1.5 μm. However, in the last years the highly efficient Raman fibre lasers were developed that emit at virtually any wavelength in the range from 1.2 to 1.5 μm [7, 8].

In addition, an efficient Raman fibre amplifier was created in which specially designed low-loss optical fibres containing a large amount of germanium are used as an active fibre [9]. This suggests that Raman fibre amplifiers will play an increasing role in fibre optic communication systems. An interesting possibility is the use of a hybrid fibre amplifier consisting of a distributed Raman amplifier and an erbium fibre amplifier. In this way, the amplification band of the width of more than 80 nm was obtained in Ref. [10]. Moreover, this hybrid amplifier possesses the better noise characteristics.

4. Optical fibres

Spectral channel multiplexing imposes severe requirements on the properties of optical fibres, first of all, on their dispersion and the effective mode area. This is explained by the fact that upon spectral channel multiplexing, the total power of all signals substantially increases, resulting in the appearance of nonlinear effects in the optical fibre such as four-wave mixing, which cause crosstalk. If N wavelengths are coupled to an optical fibre, $0.5N^2(N-1)$ new wavelengths appear due to the four-wave mixing. If the fibre dispersion in the wavelength range of the coupled emission is close to zero, the phase matching condition is satisfied and the process proceeds very efficiently.

Fig. 3 [11] shows the role of the fibre dispersion in this process. The emission from four 2-mW spectral channels is coupled into two optical fibres with dispersions $D = 0$ and 2.5 ps nm^{-1} km^{-1}. No emission at new wavelengths that would be caused by four-wave mixing is observed at the output of the fibre with the nonzero dispersion of length 50 km (the longer the optical fibre, the higher the efficiency of nonlinear processes). However, the four-wave mixing efficiently occurs in the fibre of length 25 km with zero dispersion, and more than twenty new wavelengths are distinctly observed. This imposes the following requirements on optical fibres used in multiplexed systems. Their dispersion should be nonzero (but not very large) at the carrier emission wavelengths and its wavelength dependence should be weak.



a

b

Figure 3. Emission spectrum at the output of optical fibres with dispersion $D = 0$ (a) and 2.5 ps nm^{-1} km^{-1} (b) upon excitation by emission from four spectral channels near 1546 nm.

Recall that to increase the data transfer rate in communication systems with one spectral channel, optical fibres with the zero dispersion were required. Such, the so-called zero dispersion-shifted fibres (DSF), have been designed. Due to the structure of these fibres, the dispersion zero was shifted in them from a wavelength of ~ 1.3 μm to 1.55 μm. As a result, the special so-called nonzero-dispersion-shifted fibres (NZDSF) were designed for multiplexed systems.

The role of nonlinearity can be also decreased by increasing the core diameter of a single-mode fibre or, more exactly, by increasing the effective area A_{ef} of the mode. In this case, the signal intensity decreases, resulting in a substantial reduction of nonlinear effects. Such single-mode optical fibres with the effective mode area $A_{\text{ef}} > 80$ μm^2 have been already created and are used in experimental multiplexed systems (see, for example, [12]).

However, because of a specific structure of such fibres, the mode field distribution in them differs from a Gaussian (large gradients in the light intensity distribution), resulting in a stronger acoustic response caused by electrostriction [13]. It is known that large radial gradients of the intensity of optical pulses in single-mode fibres result in electrostriction excitation of transverse acoustic waves in them. This causes a temporal perturbation of the effective refractive index and the interaction between optical pulses, resulting in the restriction of the data transfer rate [14].

The above-listed advances in the development of light sources, optical amplifiers, optical fibres, and other elements of multiplexed systems allowed all large telecommunication companies to design communication systems featuring the bit rate exceeding 1 Tbit s^{-1}. Below, the results of relevant papers reported at OFC'99 and ECOC'99 conferences on fibre optic communication held in 1999 are briefly summarised. For each of the papers, the following parameters of the system are presented: The data transfer rate per channel and the number of channels; light sources; the difference of frequencies (wavelengths) of adjacent channels; the optical amplifier type; the data transfer range and the fibre type.

1. S Kawanishi et al. 3 Tbit s^{-1} (160 Gbit s^{-1} × 19 ch.) OTDM/WDM Transmission Experiment. NTT Network Innovation Labs, Japan (OFC'99): 160 Gbit s^{-1} × 19 channels; supercontinuum + optical filters; $\Delta\nu = 480$ GHz ($\Delta\lambda = 3.6$ nm); an EDFA amplifier (telluride glass fibre); 70-nm band; 40 km, zero dispersion-shifted fibres (DSF).

2. T Naito et al. 1 Tbit s^{-1} WDM Transmission over 10 000 km. Fujitsu Labs, Japan (ECOC'99): 10 Gbit s^{-1}× 104 channels; 44 distributed feedback (DFB) diode lasers (1544.37 – 1561.83 nm) + 60 DFB diode lasers (1575 – 1600 nm); $\Delta\nu = 50$ GHz ($\Delta\lambda \approx 0.4$ nm); an EDFA amplifier (C and L bands) with the band 17.3 nm + 24.8 nm = 42.1 nm; 10 127 km, optical fibres with large effective mode area.

3. T N Nelson et al. 1.6 Tbit s^{-1} (40 × 40 Gbit s^{-1}) transmission over 4 × 10 km nonzero-dispersion fiber using hybrid Raman erbium-doped amplifiers. Bell Labs Lucent Technology (ECOC'99): 40 Gbit s^{-1} × 40 channels; 40 DFB diode lasers (1530 – 1562 nm); $\Delta\nu = 100$ GHz ($\Delta\lambda = 0.75$ nm); an EDFA/Raman amplifier with the 32-nm band; 4 × 100 km, nonzero-dispersion-shifted fibres (NZDSF).

4. H Suzuki et al. 25 GHz-spaced. 1 Tbit s^{-1} (100 × 10 Gbit s^{-1}) Super Dense-WDM Transmission in the C Band

over a Dispersion-Shifted Fiber Cable Employing Distributed Raman Amplification. NTT Network Innovation Labs, Japan (ECOC'99): 10 Gbit $s^{-1} \times 100$ channels; 100 diode lasers (1540 – 1560 nm); $\Delta\nu = 25$ GHz ($\Delta\lambda \approx 0.2$ nm); Raman amplifier; 4×80 km, DSFs.

5. J -P Elbers et al. 3.2 Tbit s^{-1} (80×40 Gbit s^{-1}) Bidirectional DWDM/ETDM Transmission Siemens AG (ECOC'99): 40 Gbit $s^{-1} \times 80$ channels; 80 diode lasers (1531 – 1562 nm, 1569 – 1601 nm); $\Delta\nu = 100$ GHz ($\Delta\lambda \approx 0.75$ nm); an EDFA amplifier (C and L bands); 40 km, standard optical fibres.

6. S Bigo et al. 1.5 Tbit s^{-1} WDM transmission of 150 channels at 10 Gbit s^{-1} over 4×100 km of Teralight fiber. Alcatel Corporate Research Center, France (ECOC'99): 10 Gbit $s^{-1} \times 150$ channels; 150 DFB diode lasers [80 (1530 – 1561 nm) + 70 (1574 – 1603 nm)]; $\Delta\nu = 50$ GHz ($\Delta\lambda = 0.4$ nm); an EDFA amplifier (C and L bands); 4×100 km, optical fibre with an optimised dispersion.

These data show that various approaches were used to create communication systems providing the data transfer rate above 1 Tbit s^{-1}. These methods differ in the number of spectral channels and capacity of individual channels, the optical amplifier type (EDFA, Raman amplifier, hybrid Raman amplifier + EDFA), type of an optical fibre (standard single-mode fibre, DSF, NZDSF, fibres with large A_{ef}), and the light source type. This demonstrates a reliability of the elemental base and a great potential of fibre optic multiplexed communication systems.

5. Conclusions

There is no doubt that fibre optic communication systems featuring the bit rate above 1 Tbit s^{-1} will find commercial applications already in the nearest years. However, it is clear already now that even such high data transfer rates will not satisfy the increasing demand of the society in the data acquisition.

At present, a moving force in the development of data communication systems is Internet. In 1998, the number of the Internet users was 25 millions, in 1999 – 144 millions, and beyond a doubt, this number will increase by an order of magnitude in the near future*. A portable PC connected to Internet will be as necessary and available for receiving information, recreation, and communication as a TV set or telephone.

Are there the ways to further drastically increase the capacity of fibre optic communication systems? They exist, and the most direct of them is the broadening of the spectral region for the data transfer. Fig.4 shows the spectrum of optical losses of a silica fibre. The numbers 1 – 5 denote the so-called transparency windows where the optical communication was performed during its development (1 – 3) and where the data transfer will be performed in the near future (4, 5). Almost all the modern communication systems operate at the wavelengths near 1.3 and 1.55 μm, i.e., in the second and third transparency windows.

Modern multiplexed systems operate in the spectral region from 1530 to 1610 nm of the width of about 80 nm. The dotted curve in Fig. 4 shows absorption caused by hydroxyl groups in silica. Advances in the technology of optical fibres resulted in the elimination of the hydroxyl absorption band, and now the spectral region between 1200 and 1700 nm, in which optical losses do not exceed 0.3 dB km^{-1}, has a width of about 500 nm. The use of this entire region for the data transfer will result in a drastic increase in the capacity of fibre optic multiplexed communication systems.

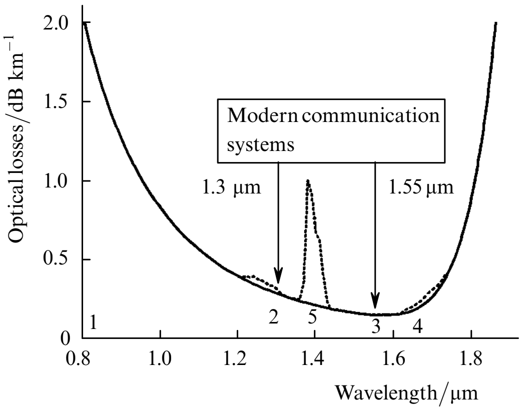


Figure 4. Spectrum of optical losses in an optical fibre.

Setting the wavelength difference between adjacent channels and the bit rate for an individual channel equal to 0.2 nm and 160 Gbit s^{-1}, respectively (the values that have been achieved already), we obtain the number of multiplexed channels equal to 2500 and the total bit rate equal to 400 Tbit s^{-1}, or 0.4 Pbit s^{-1}. Taking into account a rapid progress in the development of fibre optic communication, we can predict with confidence that the use of the spectral region between 1.2 and 1.7 μm will provide in the future the bit rate of the order of ~ 1 Pbit s^{-1}. It is clear that to create such communication systems, comprehensive fundamental studies and the development of a new elemental base will be required. In particular, an optical amplifier with an amplification band with a width of about several hundreds of nanometers will be needed.

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[*] The number of the Internet users registered in Russia in 1999 was 2.5 million.

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