Metrological Applications of Optical Reflectometry: A Review

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***Abstract*—This paper describes the state-of-art features of special optical fibers and integrated-optical circuits distributed parameters study by methods of optical reflectometry. Attention is paid to the study of the internal structure of fibers that preserve the polarization of the introduced radiation, active optical fibers, and waveguides inside the integrated chips, optical circuits, and other technological created media.**

Index Terms—**Active optical fibers, integrated optical circuits, metrology, optical reflectometry, optoelectronic circuits, special optical fibers**

I. Introduction

Optical reflectometry methods have found their wide applications in various fields of science and technology [1], [2]. Without a doubt, the most popular and dynamically developing area of optical reflectrometry is the field of distributed fiber-optic sensors [3], [4]. Optical reflectometry originated as a way to study the signal attenuation coefficient in optical fibers, communication cables and telecommunication networks built on fiber optics. This instrument is not only a way to study the distribution of signal losses in a fiber, but it can also be a flexible sensor system capable of capturing mechanical stresses, temperatures, vibrations and other physical quantities at each point of the fiber, and therefore – be the "nerve" of the object where the light guide (fiber) is laid.

Technically, this method is implemented by probing the media under test – in most cases, optical fibers, cables, and integrated optical or optoelectronic circuits – most often with an infrared signal with specified properties, usually changing in time according to a known law. The wavelength, optical power, polarization state and other parameters can vary. Further, the portion of light that has returned from the propagation media back (scattered by small inhomogeneities or reflected from dramatic changes in the refractive index) is studied and processed. It happens that light is scattered by an acoustic phonon [5], by molecules of a media [6] or reflected from specially designed mirrors, such as Fiber Bragg Gratings (FBGs) [7]. These data contain the entire "chronicle" of what and what location happens to the fiber and to the environment of its operation – a road, a bridge, a high-rise building, an airplane or a sea vessel [8]. Another, also quite relevant direction of reflectometry is the distributed study of fiber-optic communication lines. In the course of such work, both the single and the combined effect of the influence of various external factors, from the environment to anthropogenic influences, as well as the spatial localization of deviations in the parameters of signal propagation, can be investigated: the already mentioned attenuation coefficient of the optical signal, polarization-mode dispersion [9], etc.

Obviously, obtaining information about the physical parameters of the environment, their effect on the cable, the effect of the cable structure elements on the optical fiber is possible only if all the necessary parameters of radiation propagation at each point of the optical fiber are known for normal conditions. Of course, to some extent this issue can be solved by constant comparison of the obtained reflectogram (trace) and the one stored under normal conditions, which is done in most commercial and research systems. However, a dramatic change in the properties of an optical fiber at a single point when applied in a sensor system can cause a distorted response of the obtained value to a physical impact. Of course, the uniformity of operational parameters along the length is also important for telecommunication lines, however, at the stage of production of telecommunication single-mode fiber, almost all related issues were solved by using well-repeatable external deposition processes [10]. Thus, the use of optical reflectometry as a metrological or research tool aimed directly at studying the properties and parameters of the propagation media is currently focused in the field of special optical fibers [11], [12] and integrated-optical chips [13]. A review of exactly such works, which play one of the key roles in the creation of modern optoelectronic systems, is presented below.

II. Basic Principles of Optical Reflectometry

Speaking about optical reflectometry, it is necessary to give its basic principles and basic classification. According to its application, it can be divided as follows: laboratory research systems, installations for an industrial laboratory, stationary laboratory telecommunication

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monitoring systems, portable field reflectometers, stationary units for interrogating sensor systems, field units for interrogating sensor systems. By the type of recorded scattering: Rayleigh, Brillouin, Raman. By the type of radiation source used: coherent and low-coherent. Various parameters may differ – radiation wavelengths, methods of coding and signal processing, element base. However OTDRs can be divided "globally" according to the principle of signal registration: in the time domain and in the frequency domain.

In the vast majority of cases, an optical time domain reflectometer (OTDR) uses a wide or narrow spectrum signal at one stable wavelength (except for chirped pulses in a distributed acoustic sensor [14]). Such a signal will certainly change in time. The simplest and most often used methods of its modulation to create a pulsed mode are: by using amplitude or acousto-optic and other modulators [15], by modulating the pump current or using a pulsed mode in a fiber laser [16], [17]. The pulse duration is usually three or more orders of magnitude less than its duty cycle – this is necessary so that the pulse, having passed through a fiber coupler or circulator and scattered in the fiber on conglomerates of silicon and germanium dioxide frozen in quartz, has time to return back through the same coupler, to the photodetector and not intersect with the next pulse. In the simplest case, the time chart of such a signal is the reflectogram in the time domain and characterizes the attenuation coefficient of the optical signal along the length of the fiber, splices, reflections, and fusion-spliced joints. If the reflectometer is coherent, then instead of an attenuation pattern, the researcher usually sees an interference pattern, which is essentially a "spatial fingerprint" of the fiber in a particular state.

In general, the Optical Frequency Domain Reflectometer (OFDR) has the same structural elements, but the principle itself implies the use of a signal constant in intensity, linearly or according to another law changing its frequency over time [18], [19]. In this case, the source must be coherent, and the instrument itself must contain an interferometer: for example, Michelson's or Mach-Zehnder's. This is necessary in order for the signal sent to the fiber to interfere with the signal already scattered in the fiber and passed a certain distance back on the photodetector. The frequency difference of these signals, and hence the frequency of the interference beats, in this case will be proportional to the distance from the interference place within OFDR to the place where the signal is scattered. If these signals were in the acoustic range, and the human ear would pick them up, then the only measure of such a distance would be the ear for music: namely, the ability to distinguish between musical intervals. Unfortunately, the photodetector, preamplifier and all further converting part are deprived of this talent, therefore the frequency of the interference beat in the frequency domain reflectometers is determined by the fast Fourier transform. Both methods (OTDR and OFDR) give approximately the same data, albeit in different ways. A significant percentage of methods for obtaining data on different types of scattering, methods of sensing and information processing are suitable for successful implementation in the time and frequency domains both.

The basic principles of optical reflectometry are schematically shown in Fig. 1.

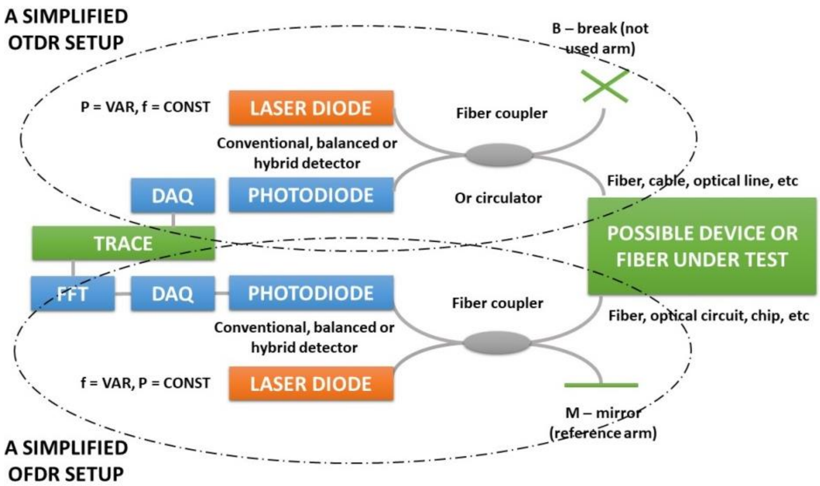


Fig. 1. Basic principles of optical reflectometry (schematically).

III. Reflectometry of Polarization Maintaining Fibers and Other Passive Special Light Guides

The polarization maintaining fibers (PM-type optical fiber) are widely used in fiber-optic sensors – most often, in fiber-optic gyroscopes, and also sometimes in telecommunications, in other optoelectronic devices. The possibility of maintaining the initial state of radiation polarization in such fibers is provided by the introduction of special structural elements that create mechanical stresses in the core along the entire length of the optical fiber [20], [21]. Due to the presence of these complex structural elements, as well as due to the use of a more flexible, but less controllable process of modified chemical vapor deposition (MCVD) [22], the uniformity of the spatial distribution of the main properties of such optical fibers is not always ideal. These properties include the polarization "not-maintaining" parameter (h-parameter), modal birefringence, and the attenuation coefficient of the optical signal. At the very beginning of such studies, fiber probing was carried out on typical Rayleigh reflectometers equipped with a polarizer at the instrument output, which, when the scattered radiation moved backward, worked as an analyzer [23]. In this case, with the input of radiation into one of the two polarization axes, it was possible to obtain and study reflectogram (trace) of the corresponding axis. This scheme was returned to in later years [24], including with the aim of collecting statistics [25]. In the last-mentioned work, it was hypothesized that some abstract defect present in the reflectograms corresponding to different input angles, but hidden in the noise, is visualized by establishing a correlation between these data. The efficiency of the technique was confirmed for only a few samples, and the work was not further developed due to the laboriousness and duration of scanning over a large number of input angles and the dubious possibility of searching for relationship between the correlogram bursts amplitude with the actual deviations of the polarization characteristics. That is why this research group later chose the strategy of studying only two states of polarization: the fast axis and the slow axis, which led to a quantity that has a clear linear relationship with the h-parameter [26]. Unfortunately, a detailed comparison of this approach with the widely known method of white light interferometry [27], [28], which should be carried out on a large number of samples, has not been presented in the literature. By similar methods, but using Brillouin scattering, one can obtain the spatial distribution of the modal birefringence [29], [30]. In these works, the approach to which was guided by a similar technique in crystals [31], a simple relationship was used between the refractive index and the Brillouin Frequency Shift (BFS). The described method, despite the simplicity of implementation on commercial equipment, does not allow to measure the desired parameter's absolutely accurate values due to the difficulty in selecting the correct values of the speed of sound in each of the samples. The methods described above dealt mainly with straightforward solutions to the problem using minimal modifications of popular research equipment. Below are the works in which new experimental stands were created to obtain the desired distributed characteristics.

Studies carried out on coherent phase-sensitive reflectometry setups, both in the time domain and in the frequency domain, look promising. One of such installations is presented in [32]. The method is also based on the correlation comparison of polarization states, but with respect to the Rayleigh scattering spectra. In this case, the coordinate of the maximum of the cross-correlation function will be proportional to the difference in refractive indices for the two axes at each point of the fiber. This method makes it possible to observe fluctuations in long-length samples, but the use of a meter pulse does not allow obtaining a spatial resolution of less than one meter. This disadvantage is easily overcome by the frequency domain method. For example, in [33], the length of polarization beats in an anisotropic optical fiber was measured by probing with continuous radiation with a linearly sweeping frequency. Frequency-domain reflectometer, which have no optical dead zones, opens up the possibility of conducting such a study with an extremely high resolution. However, along with the obvious advantages, it is necessary to note a rather significant drawback of this approach: the study requires strict control of the actual frequency sweeping function, which is carried out by software and hardware. Of course, this is implemented in many research and commercial systems, however, it has a rather noticeable impact on the cost of the setup. Noteworthy is the method, which to some extent is a hybrid of phase-sensitive reflectometry of the time and frequency domains [34]. The setup for measuring distributed birefringence, created by the authors of [34], is shown in Fig. 2.

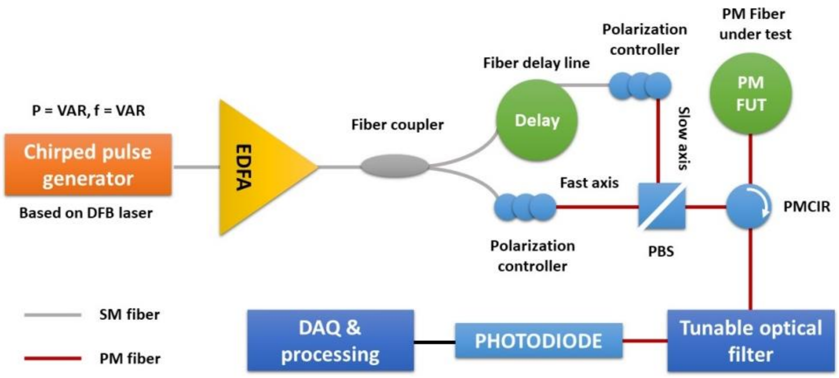
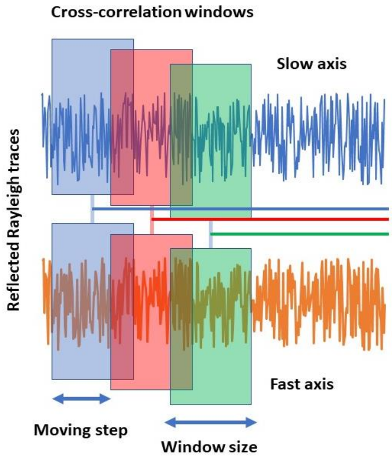
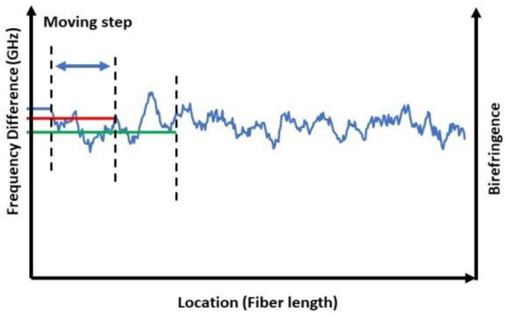


Fig. 2. Setup for distributed birefringence measurement (adapted from [34]).

The use of a chirped pulse generator and subsequent correlation processing of the signal made it possible to reliably observe the modal birefringence spatial fluctuations of the order of 10^{-9} (Fig. 3). Similar to the classical spectral method of integral measurement of birefringence, in this case the actual, non-indirect measurement of the desired quantity also takes place. Unfortunately, this undoubtedly accurate and promising method needs the frequency chirp, which cannot always be realized and controlled by available methods. Another noteworthy method is the distributed measurement of birefringence using a dynamic transient Bragg grating (TBG) [35]. A TBG was created by two short pump pulses in the slow axis of the polarization maintaining fiber, and then the birefringence-related TBG spectrum is mapped by using a probe pulse inputted to the fast axis, where the local birefringence can be calculated using the birefringence induced frequency shift. Two types of widely used polarization maintaining fibers, bow-tie and Panda-type fiber, with a length of 8 m were studied at a spatial resolution of 0.2 m, and the results showed that the birefringence features a periodic variation, and their variation ranges are approximately 2.4×10^{-6} and 1.3×10^{-6} along the tested fibers, respectively. This approach also seems promising, however, it may not be applicable when the fiber is tested as a part of an optoelectronic circuit, some of the components of which are not capable of sufficiently high optical powers transmission. In addition, the method of interrogating a dynamic grating usually requires access to two free optical fiber tips (ends), which is not always possible to implement in practice.



(a)



(a)

Fig. 3. (a) Demodulation method for birefringence profile of PM fiber based on traces from slow and fast axis and (b) Birefringence profile of PM fiber. Adapted from [34].

As for the distributed measurement of the h-parameter, it should be noted that in modern practice the reflectometric methods used to solve this problem are almost completely replaced by the already mentioned techniques based on the white light interferometry principles. Such installations have found commercial implementation and widespread use among manufacturers of special optical fibers, fiber-optic sensors – in particular, fiber-optic gyroscopes (FOGs).

By the way, speaking of FOGs, one cannot fail to mention a separate type of anisotropic optical fiber distributed study: the study of fiber parameters as part of a FOG coil. In such coils, the fiber is wound in a quadrupole manner, coated with a special compound, and then undergoes a curing procedure according to special regimes [36]. The usual lengths of such fibers are from 500 m to 2 km.

The main task of the reflectometric study in this case is to identify the locations of the unacceptable mechanical effect of the fibers on each other, including those under different temperature conditions. Thus, in [37], in one of the pioneer papers, the very fundamental possibility of controlling the coil winding process using the Brillouin optical time domain reflectometry (BOTDR) method is demonstrated. Later, using the Brillouin optical time domain analyzing (BOTDA) method, which requires access to the two ends of the fiber, but with greater accuracy, the FOGs coils were studied under varying temperature conditions [38]. These studies allowed the authors to draw important conclusions about the technological regimes of creating the coil. Such methods could be used in conjunction with the white light interferometry, which is productive in fiber coils measurements [39]. The combined application of these methods makes it possible to estimate not only the mechanical stress to which the fiber in the circuit is exposed, but also the polarization parameters of the radiation and their spatial evolution by two different approaches.

Among anisotropic special fibers, a separate type can be distinguished – these are the so-called spun fibers obtained by twisting a preform in a drawing tower and having a lower birefringence compared to other PM fibers. For their distributed research, new technical solutions are often required, since some of the approaches described earlier may not be applicable. For example, the above-mentioned method of polarization-Brillouin reflectometry [29], [30] loses its accuracy with decreasing fiber birefringence. This is due to the fact that the frequency scanning step and the accuracy of its determination are limited. In this case, the smaller the difference in refractive indices at each point must be obtained, the smaller the frequency difference this value corresponds to. Due to such difficulties, this problem is usually solved by registering Rayleigh scattering. In the next work [40], the simulation based on the Jones matrix formalism was verified experimentally using two methods at once: a Rayleigh polarization reflectometer with a photon count and a polarization-sensitive frequency domain reflectometer. Almost simultaneously, similar studies were carried out by another group of researchers [41]. In further studies, scientists more often use the frequency domain reflectometry method to find the parameters of spun fibers [42]. This is due to the fact that this method usually uses polarization-sensitive components, balanced or hybrid detectors that are convenient for recording polarization characteristics, and most importantly, it has a resolution sufficient to register the so-called spun period (the fiber length enough for the 360˚-twist of fiber birefringence axes). This trend is undoubtedly promoted by the emergence of longer-range systems, while maintaining a high spatial resolution [43]. Before the appearance of such installations, the use of the OFDR method in relation to metrology of spun fibers could be considered non-destructive only formally – the kilometer lengths of fiber newly drawn from the preform had to be divided into sections of several meters.

Another type of passive special optical fibers, the parameters of which must be observed in a distributed manner, are the so-called few-mode fibers, widely used in fiber-optic sensors [44]. However, before using a fiber in a distributed sensor, it must be produced and its uniformity of optical-geometric characteristics along the length must be studied. So, in work [45] this type of fibers was investigated by the OFDR method. The authors managed to measure the differential group delay and birefringence using the spectral correlation of specially selected areas of the reflectogram. The OTDR method allowed another scientific group to measure the attenuation coefficient of the optical signal for each mode separately, by applying impact to the fiber [46]. In general, a distributed study of fibers of this type in time domain for the purpose of certification of the attenuation coefficient can be problematic due to the rather high sensitivity of the latter to various external influences. The authors of [47] analyzed the backscattering coefficients of various optical modes and, on the basis of this, created a compensation technique that makes it possible to reduce parasitic fluctuations in the reflectogram.

Another important reflectometric study of few-mode fibers is the study of their intermode Brillouin scattering spectra [48]. It allows one to observe two or more Brillouin Gain Spectra (BGS) Lorentzian peaks and to study the coupling coefficients of their central frequencies with various influencing factors, such as temperature and longitudinal deformations. The frequency shift in the stimulated Brillouin scattering spectrum for each acoustic mode is linearly related to temperatures and deformations, and the coefficients of this relationship are unique. Engineering and scientific distributed laboratory studies of such fibers make it possible to certify their sensory properties and prepare them for operation in systems that allow separate measurement of various influences.

As for classical multimode fibers, in which many more optical modes propagate, their distributed metrology was quite simple at the dawn of fiber optics and was coming down to the optical losses measurements with a Rayleigh reflectometer in the time domain. However, the rapid development of local telecommunication networks and distributed fiber-optic sensors, where multimode fibers have a fundamentally new role, has given rise to a request for a more sophisticated study of parameters. For example, the authors of [49] proposed a study of multimode fiber in the frequency domain. The study yielded the value of differential mode dispersion in the fiber, and the results were compared with measurements obtained in the time domain. Thus, the already mentioned studies of optical losses in multimode fiber can hardly be considered such an archaic task from the point of view of scientific interest. So, for example, in [50], the creation of a multimode fiber and its laboratory study to clarify the operating parameters in a future distributed sensor are presented. The group of scientists measured optical losses introduced by a 50-centimeter fiber fragment, the cladding of which was subject to etching. This fragment was placed in an environment with different chemicals at different temperatures. The experiment required recording the exact specific (per Celsius degree) attenuation coefficient of the optical signal. The commercial reflectometer used by the authors made it possible to obtain the desired value in decibels with an accuracy of the fifth decimal place. Such studies stimulate the development of experimental setups with wide dynamic ranges of recording back-scattered power using high-performance analog-to-digital converters of high bit depth.

The distributed study of the multimode and low-mode optical fibers properties is of a special interest when there is an instrumental possibility of observing the behavior and interaction of various optical modes propagating along one large fiber core. Unfortunately, in practice, this is quite difficult to implement both from the hardware point of view and in terms of digital signal processing due to the uneven distribution of optical power between lower-order modes and other modes, low signal intensity at the end of the line, and other reasons associated with individual methods of optical reflectometry. Things are different when it is necessary to investigate a special, multi-core fiber [51]. In these fibers, a separate information signal can propagate along each core, while the cross-interaction between such signals is significantly less than between modes in the common core. Controlling such fibers in an industrial laboratory is a rather non-trivial task - from injecting radiation into each of the cores, to testing the fiber in extreme conditions and then interpreting the data. So, in the next work [52], first the creation, and then the reflectometric study of a multicore fiber of the so-called D-shape is considered (Fig. 4).

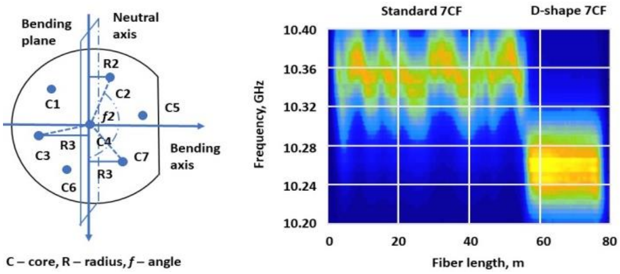


Fig. 4. Cross-section of a D-shape fiber and a Brillouin trace of one of its peripheral cores in comparison with the standard 7CF (adapted from [52]).

The goal of the study was to evaluate the suitability of this design for distributed curvature detection using Brillouin scattering. Initially, all 7 fiber cores were made by MCVD process as separate preforms. They were then inserted into pre-prepared holes in a quartz rod. Further, with the help of grinding, a D-shape was achieved, which, according to the authors' idea, should have improved the required sensory properties due to the fiber self-orientation. The authors of the work provide a Brillouin reflectogram (trace), which displays the BFS of the peripheral core of sequentially connected multicore fibers, the last of which has a D-shape. It can be seen that the fiber’s BFS fluctuations are much lower than that of the standard fiber. This laboratory study demonstrates the potential for higher stability and high measurement accuracy when using this fiber as a distributed curvature sensor. It should be noted that similar studies were carried out earlier, on typical multicore fibers, using the technique of frequency domain reflectometry and other methods [53]-[55]. No doubt they do not require the creation of special variation of multicore fibers, but they have lower precision.

Another type of special optical fibers important for the modern optoelectronic industry is microstructured optical fibers, which are used as structural elements of circuits, for generating supercontinuum, as optical sensors, etc. [56]. They usually have an extremely complex structure and, depending on the design and production technology, as the main method of radiation propagation, they can have both the law of total internal reflection and photonic band gaps. In such fibers, the attenuation coefficient of the optical signal at the wavelengths used in typical commercial OTDRs is quite high in some cases, which imposes serious requirements on the dynamic range of the device. Moreover, the future field of application of the fiber often dictates the need to obtain information not only about the transmission or generation characteristics, but also about the sensory properties. For example, in [57] the ability of a microstructured fiber to register temperature in a distributed manner with stable accuracy in regimes of various X-ray radiation exposure has been studied in laboratory conditions. The authors used the method of inverse Fourier spectra correlation in the frequency domain, already mentioned in this review. It has been shown that the fiber under study, subjected to different regimes of X-ray radiation exposure, allows one to obtain the temperature by the OFDR method with invariable accuracy (for every single X-ray radiation regime), while the systems based on Brillouin and Raman scattering give a measurement result that strongly depends on radiation [58], [59].

It is interesting to use one of the types of microstructured fibers – photonic crystal fibers – for measuring hydrostatic pressure. Paper [60] demonstrated a distributed laboratory study of such a fiber. This study notes that photonic crystal fibers can be made pressure sensitive by optimally positioning their internal microstructure. In this article distributed birefringence and hydrostatic pressure in photonic crystal fibers with high birefringence are measured using setup based on phase-sensitive optical reflectometry in the time domain. The response to the hydrostatic pressure of two specialized photonic crystal fibers, sensitive to pressure, in the range from ~0.8 bar to ~67 bar with a spatial resolution of 5 cm was investigated. Different responses of the slow and fast axes of polarization of the studied fibers to the applied pressure were found. These responses were –219 MHz/bar and –95.4 MHz/bar. These values are from ~ 3.8 to ~ 8.8 times greater than those previously demonstrated by pressure distribution measurements with other photonic crystal fibers. Such studies help to reveal the possibility of separating temperatures and deformations in anisotropic fibers of any type, probed by any phase-sensitive or spectral-sensitive reflectometers [61].

IV. Reflectometry and Similar Studies of Active Fibers

Active optical fibers have found wide application in various fields of optoelectronics, especially in fiber lasers and amplifiers [62]-[64]. Typically, active fibers are made by MCVD method, by impregnation, or other techniques. In the course of the technological process, the fiber core is doped with multicomponent additives having rare earth metals: erbium, ytterbium, and holmium; quite often, aluminum oxide is often used with them; sometimes bismuth is the main component of the active fiber. The appearance of such substances in the fiber core leads to a dramatic increase in the optical attenuation coefficient: if in single-mode telecommunication fibers, the attenuation can be about 0.2 dB/km, then in active fibers, say, doped with erbium, this value can be about 30 dB/m. Again, this places serious demands on the dynamic range of any measurement system. Globally, distributed measurements of active fibers can be divided into the following groups:

1. Study of the BFS spatial variation in relatively short active fiber lengths, usually corresponding to the circuit length of a fiber laser or amplifier. Sometimes the dynamic range of the reflectometer is not enough to build a spatial trace, so the detecting unit accumulates one integral value over time. It is believed that the BFS in any fiber is its actual "fingerprint" – a value that characterizes the overall optical-geometric parameters of the fiber, including the correctness of the active dopant deposition regimes. Comparison of the obtained value with the reference value is relevant for scientific and industrial laboratories engaged in the production and adjustment of technological processes for the manufacture of active fibers.

2. Investigation of approximately the same lengths of active fibers by the method of frequency domain reflectometry. This can be done for various reasons, including to establish the exact length of the fiber. Also, the method is indispensable when the high-resolution study of unbreakable optical scheme containing the circuits of lasers and amplifiers is required. The method can be applied by developers and manufacturers of optoelectronic devices.

3. The extended length sections of active fibers OTDR studies. It is usually performed using high-power optical pulses emitted at the wavelength of maximum transparency of the fiber. It can provide information on “gray” losses and, indirectly, on the distribution of the active dopant concentration, as well as on the length of the fiber under study, accurate to the pulse duration. The method finds its application in laboratories performing a full cycle of creating active fibers.

So, let's consider several scientific works that clearly characterize the methods of research described above. Thus, a group of authors [65] set themselves the task of a detailed study of the behavior of the BFS of erbium fibers under various conditions. Later, in [66], the BGS of these fibers were obtained at 1.55 μm without pumping, and the BFS and its dependences on strain and temperature were studied. Clear BGS was observed for the Nd^{3+}-doped and Tm^{3+}-doped fibers, but BGS was not detected for the Sm^{3+}-doped and Ho^{3+}/Tm^{3+} co-doped fibers due to high attenuation at the propagation wavelength and small Brillouin gain coefficients. The BFS of the Nd^{3+}-doped fiber was ~10.82 GHz, and its strain and temperature coefficients were 466 MHz/% and 0.726 MHz/K, respectively. As for the Tm^{3+}-doped fiber, the BFS was ~10.90 GHz, and its strain and temperature coefficients were 433 MHz/% and 0.903 MHz/K, respectively. In [67], the BGS of Ho^{3+}-doped fiber was obtained with a commercial analyzer and its sensitivity to temperatures was studied. In parallel, the temperature dependence of the attenuation coefficient at a wavelength near the 1080 nm was investigated. The possibility of carrying out a distributed study with spatial scanning was ensured by the optimal choice of the fiber length and holmium concentration. The paper is presented in a local scientific publication and does not have an English-language version.

The study [68] also used a commercially available Brillouin reflectometer. Its objective was to certify the BFS for different types of optical fibers including, active ones, under normal conditions, for further automatic identification on the reflectogram (trace). As in the previous work, the provision of spatial scanning was ensured by selecting the optimal length. In general, unfortunately, there are not so many scientific works on the study of the BFS spatial distribution in active fibers. First, this is due to the fact that not all researchers have the opportunity to study fibers with a low concentration of an active additive. Secondly, the study of ultra-short fiber lengths with BOTDR/BOTDA is not always relevant. At any significant lengths of active fibers at the end of the fiber line, the signal is usually extremely noisy, which does not allow one to clearly reconstruct the Lorentzian function and determine the maximum of the BGS. However, in [69], finding the BFS under conditions of an extremely noisy signal has already been tested in a computer experiment, and its use for studying active fibers was also announced there, while in [70] methods using machine learning are demonstrated; which potential of using in noisy signals processing is also high. There are all the prerequisites that such methods of signal processing will make the reflectometric studies of the active fibers BGS more accessible.

The second category of studies, mentioned earlier, where active optical fibers are investigated by methods of optical reflectometry of the frequency domain, includes one of the pioneering works published in the last millennium [71]. The addition of a pump diode emitting at a wavelength of 980 nm to the classical OFDR scheme based on a Michelson interferometer made it possible to significantly amplify the backscattered signal (Fig. 5).

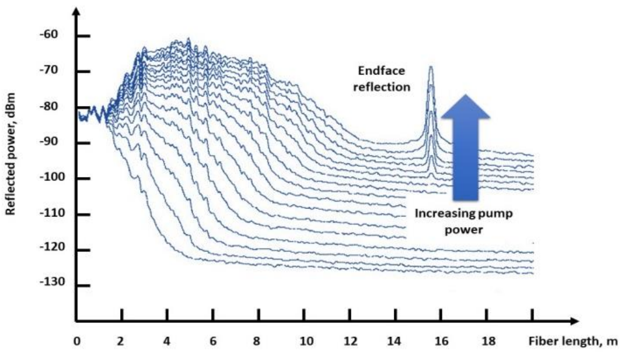


Fig. 5. Spatial trace of backscattered power in OFDR studies of erbium fiber versus pump power (Adapted from [71]).

The authors investigated two fibers with different concentrations of active erbium ions (500 ppm and 300 ppm), as well as different lengths (13 m and 6 m, respectively). Due to the coherent detection of the frequency domain reflectometer, the spontaneous emission signal was naturally filtered in the vicinity of 100 kHz. The authors revealed a serious dependence of the shape of the reflectogram (trace) on the power of the pump diode. It is noted that the potential of this technique allows it to be used for a more correct assessment of the optimal length of active fibers in each specific modification of a fiber laser or amplifier. Later, in [72], a thulium fiber amplifier was studied by the OFDR method. In addition to a distributed study of the signal level along the length of the fiber, data were obtained on the silica-to-ZBLAN fiber splice losses. Such work gave rise to research in which not individual elements are studied, but a whole circuit consisting of fiber and other components. More details about such experiments will be given in the third part of this review.

As concerned works, announced in the beginning of the chapter, devoted to the distributed study of the characteristics of rather extended fragments of active fibers, we have found only one such study [17]. Perhaps this is due to the fact that new “players” in the special fibers market (that is, their manufacturers) appear rather rarely. And those of them that have been producing active fibers for a long time, not so often fundamentally change technological regimes requiring total control during the process. However, in the course of the creation or development of flexible manufacturing, such tasks begin to arise. And if in the process of preparing the components and at the stage of a preform creation, the spatial distribution of chemical substances in the sample can still be controlled in some known ways [73], [74], when the sample has a length of several kilometers and optical losses of tens of decibels, the distributed study by reflectometry methods becomes a serious challenge. So, to solve this problem, an all-fiber reflectometer based on a pulsed ytterbium fiber laser with a passive holmium shutter was designed (Fig. 6).

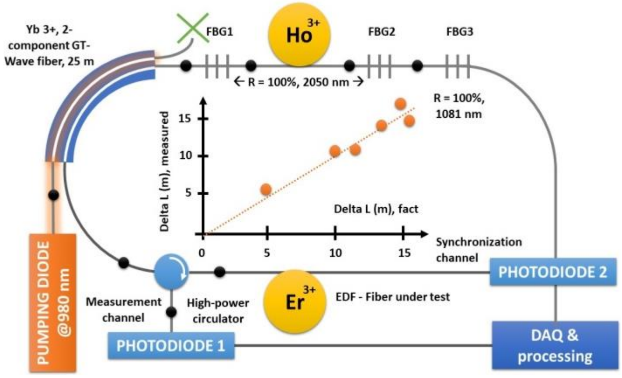


Fig. 6. The all-fiber reflectometer and the result of measuring the erbium-doped fiber length (Adapted from [17]).

Undoubtedly, an acousto-optic modulator that transmits high powers could be used to modulate the optical signal, but the all-fiber version was chosen by the authors as a more affordable and, in their opinion, simple solution. The authors used a relatively suitable wavelength for propagation through holmium glass in the spectral range of 1080 nm, which falls on the luminescence region of ytterbium. The results of the experiments made it possible to obtain, first, a fairly accurate measurement of the fiber length – with the precision of 1.82 m while the length of the entire sample about 850 m; secondly, they mentioned the potential suitability of the method for describing the "gray" losses along the fiber length, and - subsequently - absorption losses in the region of 1530 nm. However, presumably nonlinear effects in the line did not make it possible to reliably quantify the indicated values.

V. Reflectometry of Optoelectronic Assemblies, Circuits and Integrated Optical Chips

Reflectometry of optical circuits is a rather important engineering tool for their diagnostics. Of course, each of their components can be subjected to a distributed study separately - a type of reflectometry suitable for this particular component, with the choice of optimal probing and data processing parameters. However, there are very few cases when the 100% performance of each component can be judged on the failure-free operation of the entire chain. In this case, it is necessary to know how efficiently the light is introduced from one component to another: what are the optical losses at the junction [75], [76]? How powerful back reflection is observed at the interface between the media [77]? What is the polarization extinction of the splice [78] and many other parameters? Moreover, part of the circuit can be simply destroyed during the experimental selection of operating regimes - for example, when sufficiently powerful pulses pass, the core can burn out [79], and this part of the circuit must be localized without dismantling it. Finally, a banal fiber break can occur.

Of course, the scale of fiber and integrated-optical components (polarizers, circulars, splitters, fiber Bragg gratings, etc.), which are most often used in optoelectronic circuits, is within few centimeters. While the fiber parts connecting these elements can be several meters long. Moreover, fiber circuits, delay lines and other similar elements, the length of which can be several kilometers, can also be included in the chain. It is easy to assume that the optimal method for testing such schemes can be optical reflectometry of the frequency domain, the spatial resolution of which is sufficiently high and does not depend on the pulse duration, which is replaced by frequency tuning in the OFDR method, as already noted.

In one of the pioneering works of 1997 [80], the main physical principles were given and the ranges of the OFDR method were estimated as applied to the problem of monitoring optical circuits. The limits of the presented approach were described, as well as dynamic range and sensitivity, and polarization effects were discussed. The most important limitations on spatial resolution, phase noise and noise floor were given. It was shown for the first time that nonlinearities in the frequency sweep function limit not only the resolution, but also the maximum distance measurement range. The authors were among the first to explain the origin of fading noise in the signals of Rayleigh backscattering in OFDR, and the method for eliminating them, and presented there, made it possible to carry out accurate measurements of optical losses. As for the sensitivity of the method, it was found that the background noise of measurements is due to variations in the radiation intensity introduced by the laser control circuit. This knowledge became the basis for newer research.

For example, in a later work [81], the capabilities of the method were significantly expanded. The authors have shown that the availability of high-precision tunable laser sources and modern methods of computation and data acquisition can expand the provision of high-resolution measurements of optical circuits having rather high lengths. It is noted that the modifications of the frequency domain reflectometry method described in this work make it possible to study entire optical circuits without breaking them due to the possibility of transmitting long fiber pigtails. The technique described in this paper appeared to be suitable for optical chain lengths of more than 200 m, while a spatial resolution of about 100 μm was demonstrated. An interesting feature of this work is also the fact that already in those years the authors were guided by the high-speed measurement, which can be useful in the study of optical circuits subjected to variations in external influences. That is why in their work they presented the data obtained in a single measurement (for one frequency sweep of the laser). Further, however, it was noted that for high-precision measurements under stationary conditions, it is nevertheless necessary to accumulate a certain number of measurements. Unfortunately, this work focuses only on the canonical fiber Bragg grating, while all the other optoelectronic components remained outside the scope of this study. Also, an important limitation of the method is given in the work, which is also relevant for modern systems: all the components of the optical circuit under study should not significantly distort the optical spectrum in the range of laser tuning of the reflectometer in the frequency domain.

In a fairly new work, researchers continue to improve the metrological characteristics of the system [82]. In this case, the tasks were dictated not only by the need to obtain correct measurement data on the components of the optical circuit: this was done in view of the growing demand for automatic identification of fiber components and optical fibers (Fiber ID). For this, the so-called physical unclonable function (PUF) is used, which is a code (key) formed at the molecular level of a fiber, integrated-optical component or a fragment of a fiber line, which, among other things, must be taken into account when studying optical chains [83], [84]. To solve these problems, the authors again paid great attention to the stability of the laser sweeping function. The authors also note that in order to achieve this goal, it is necessary to stabilize as much as possible not only the sweeping rate but also the initial frequency of the semiconductor laser. The paper presents a technique that solves the indicated problems algorithmically, while optimization of the post-processing program code makes it possible to obtain data much faster. As one of the illustrations of the effectiveness of the method, the authors demonstrate a reflection that is actually present in the optical circuit, but remains invisible without the application of their method.

As already noted, it is important not just to observe the parameters of the optical chain - in some cases one needs to observe the evolution of these parameters in time. This is necessary not only for testing the line, but also for monitoring the commutation of its individual elements. The paper [85] investigated the possibility of automatic switching of an integrated optical circuit and PM-fiber by the method of optical reflectometry in the frequency domain. The OFDR method made it possible to monitor the quality of the connection by the reflection at the input to the chip and at its output. The reflectometer was designed on the basis of a Michelson interferometer. The measuring arm of the interferometer was a line formed by an optical fiber and a channel waveguide of an integrated optical circuit. The integrated optical circuit with proton-exchange channel $LiNbO_3$ waveguides was polished at an angle of 10°, and the tip with a fiber light guide was polished at an angle of 15°. Experiments on the alignment of the optical fiber and the waveguide were carried out and analyzed. It was shown that the amplitude of the signal reflected from the far end of the waveguide was determined by the size of the longitudinal and lateral displacements between the fiber and the waveguide. During the experiments, the accuracy of the alignment process was established for each of the axes. Despite the fact that an ordinary laboratory oscilloscope capable of averaging tens, at best hundreds of measurements, was used as a data acquisition board for the OFDR, this was enough to ensure the operation of the system in real time.

The OFDR operating speed was also important in the experiment, where an integrated-optical chip, which in functionality is a phase modulator of optical radiation, was investigated by a frequency domain reflectometer for the purpose of waveguide channel “shut-down” due to the pyroelectric effect [86]. The high resolution of the used commercial OFDR unit made it possible to obtain a spatial scan of the entire chip, check it against the topology known from the product passport, and also study the behavior of each integrated-optical circuit fragment during a fast heating started at the low-temperature region. The study confirmed that the studied effect is distributed, and refuted the initial idea that it is most pronounced in locations corresponding to topological elements, such as, for example, Y-splitting of channels.

In article [87], the authors report on the OFDR device, in which the interferometric part is monolithically integrated together with the device under test. The authors have emphasized the obvious advantages in terms of compactness and performance. Experimental verification was performed by interrogating an array of waveguide gratings (AWG) on a silicon nitride substrate. The results show that the proposed circuit is the first step in the search for a universal measurement and research concept for integrated devices. The researchers localized the strong phase deviations in the surveyed array waveguides. This localization, for unknown reasons, was not possible with an external OFDR installation. The authors called the IOFDR system they developed - integrated OFDR. The results of its work are shown in Fig. 7.

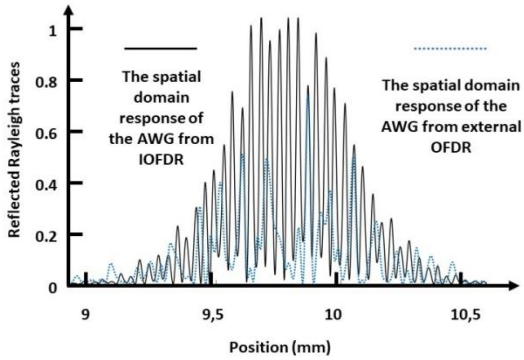


Fig. 7. IOFDR data obtained by the AWG on a silicon nitride platform interrogation. Adapted from [87].

VI. CONCLUSION

This review focuses on a series of works devoted to distributed laboratory research of various types of optical fibers, circuits of optoelectronic devices, and integrated optical devices. Where possible, the authors tried to select the brightest and state-of-the-art representatives among the works in each of the review chapters. In some chapters, it was mentioned that certain works, according to the information of the review authors, had no analogues. A rather modest number of works on the subject of this review study, in our opinion, is due to the following possible reasons:

1. Currently, the trends in the development of most types of distributed measurement systems are determined by the needs of the distributed fiber-optic sensor industry, as well as the demands of the telecommunication industry. Fortunately, this to some extent stimulates the development of distributed optical metrology.

2. Often, distributed research of a particular fiber or optical chain is a stage of deep research and development, preceding the appearance of a commercial version of a particular sensor or another product. Even among the works shown in this review, there are examples of such studies, where a special optical fiber is extensively investigated in the laboratory, while the ultimate goal of all described actions is the development of a sensor. For obvious reasons, such studies are rarely published in the open press.

3. If we are talking about special optical fibers produced in academic labs or on an industrial scale, in a scientific laboratory or a factory workshop, then distributed studies of even individual samples become part of technical quality control, and therefore the entire production process. The specificity of some special fibers application adds complexity to the situation. Thus, not many scientific studies that have been carried out, reach stage of publication. Fortunately, many types of special fibers find their application in science, therefore, the details of their research are published mainly by scientists from higher educational institutions and academic structures.

Also we studied the statistics of work on reflectometry at the International conference "Optical Reflectometry Metrology and Sensing" in recent years (Fig. 8). This is one of the few international conferences that has declared a special focus on fibers and optoelectronic circuits distributed research in the laboratory. Based on these data, there is some decline in fully laboratory studies, which also include works on setups modification, like [88]-[90]. However, it is noteworthy that such studies for the most part become part of a larger, sometimes "in-field" work, including testing and research at later stages of development [91]-[95]. This means that the trends in research are not changing as much as the manner of their presentation in scientific works.

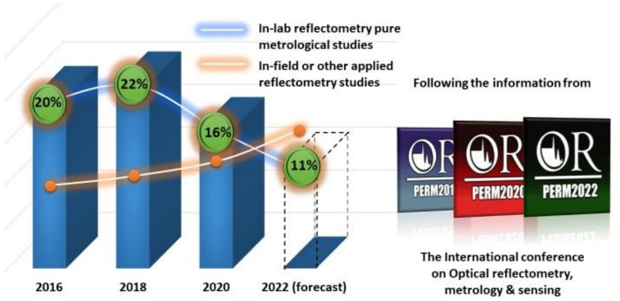


Fig. 8. Tendencies in state-of-art reflectometry following the conference stats.

Based on the fact given above, the review authors believe that not very large number of publications is not equivalent to the small number of works in this direction, and sometimes a review of the actual knowledge in this area, similar to this paper, needs to be carried out. In the next similar study, the authors plan to pay attention to patents registered in this area. Such work will be a logical continuation of this article, characterizing as not so scientific achievements as a purely practical ones.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yu. A. Konstantinov – general conception, all parts, figures design; R. S. Ponomarev – part V, corrections of all parts; F. L. Barkov – final production of all parts.

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