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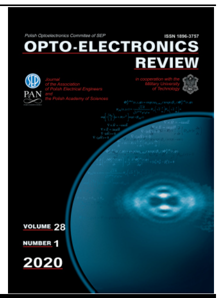

Phase coding of information in the optical fibre sensor

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Abstract

Determining the dependence of phase difference modulations between light pulses in a modified Mach-Zehnder interferometer was used to develop an optical system coding the information and working as an eavesdropping sensor for an optical fibre information exchange system. The basic challenge in the system development is to maintain stable operation in changing environmental conditions, as well as to ensure optimal parameters of the phase modulator. The system was tested for various many-kilometer long transmission lines of single-mode fibres. The research was focused on achieving the normative Bit Error Rate for the system in the 100 Mbit/s range (STM-1). Such a system can be used in commercial applications for the code key secure transmission in the physical layer of the link.

1. Introduction

In the era of globalisation a tremendous access to information which has become common, accessible, but also valuable and requiring safe, fast and high capacity transferring was enabled. This is extremely important in the critical areas of life, i.e., military, banking or personal data protection, thus, it is necessary to implement the method of data security during its transmission. Modern data exchange systems are based mainly on optical fibre technology. Therefore, various types of optical fibres cable protection were developed to avoid eavesdropping which includes fibre-optic track monitoring using fibre-optic sensors [1-3]. Newer methods of data exchange optical protection are based on distribution of the quantum key [4-7]. Important security features in this type of solution include physical data protection based on Heisenberg uncertainty. The bits are coded in the phase or polarization state of photons. By assumption, any attempt to find out the photon state, before reaching the receiving setup of the system, results in disturbing this state and, thus, breaking the BB84 protocol [8] coding rule. Safety aspects in this formula are undeniable and mathematically proven [9]. However, it should be mentioned, that such system technology is based on a modified Mach-Zehnder optical fibre interferometer configured to operate in a single-photon case. Replacing the part or the whole information in the quantum key distribution (QKD) systems requires a precise knowledge about the polarisation state and phase of photons which implies knowing direct settings of controlling devices which defines these parameters [10]. Detection on two dedicated single-photon detectors enables the binary states' identification. According to Ref. [11], there are still technical limitations of such method. It should be noted, that it is possible to eavesdrop this type of the quantum key exchange without knowledge of the broadcaster and the recipient [12]. This is caused mainly due to the detection systems' limitations.

Bearing in mind the above state of technology, the authors have attempted to develop a system that will more effectively protect data transmitted in a fibre-optic transmission channel. As the start position, the use of the data exchange scheme was adopted as in the (QKD) systems, but with crucial changes. The use of a single-photon transmission for the pulsed laser source was abandoned in order to suppress the technological limitations of single-photon detection. Therefore, the idea of data exchange security based on the photon uncertainty principle was abandoned. Mathematical BB84 protocol of a given key exchange methodology was not used, as well. The basis of the system presented in the article is a technical optoelectronic designing of the system's

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operation in order to save bit information in the phase difference between two pulses of light propagating in the optical fibre path from the transmitter to the receivers. By assumption, every disturbance of the optical fibre path results in desynchronization of the mentioned phase relations and as a result, the eavesdropper automatically disturbs this information. In addition, as demonstrated by authors' team [13-14], the system in this configuration has additional sensor features enabling the alarm signal generation [15]. The crucial aspect described in the article is to learn time relationships associated with propagation of light pulses and their phase modulation in a modified optical fibre interferometer path.

2. Experimental details

2.1. *Pulse interferometer – basic concept*

The experimental setup, illustrated in Fig. 1 and described in this paper, consists of a sensor unit and a standard single mode (SM) optical fibre terminated with a phase modulator (PM) and a mirror. The classic optical fibre based Mach–Zehnder interferometer (M-ZI) using PANDA polarization maintaining optical fibre (PM type SM15-PS-U25A) was used as a sensor unit. A 1.55-µm stabilized pulsed laser (PicoQuant LDH-D-C-1550 stabilized with the Peltier cooler, marked in Fig. 1 as LAS) with the 1-ns pulse duration was used to power the system. We assume that the ordinary axis of the PM fibre is parallel to the electric field vector ($\vec{E}$) and vertical to the initial polarization of the pulses. The circulator (CIR-SM-PIPE-1550 marked in Fig. 1 as CIR) was separating the laser beam and the radiation coming back from the setup which stabilized laser's operation.

Then, the beam splitter (SPL-SM-PIPE-2x2 marked in Fig. 1 as BS) divided the beams generated by the laser into two arms of M-ZI, having the length of 1 m and 13 m for arm1 and arm2, respectively. The separation of the pulses equal to 60 ns (Fig. 1c) was assured by a 12-m difference in arms' lengths. The first arm consisted of a PM fibre that was rotated by 90 degrees and then spliced. It resulted in perpendicular direction of E field in relation to the ordinary axis of a PM fibre. Therefore, the polarization beam splitter (PBS-1x2-1550 marked in Fig. 1 as PBS) combines two separated in time pulses with perpendicular polarizations (Fig. 1b and 1c). Thus, these signals do not interfere for forward propagating pulses. PC adjusts the input polarization state so that after the radiation passes through the system, polarization state is matched to PBS. The double passage through PC is taken into account in the system operation.

A multikilometer long SM telecommunication optical fibre (1.55 µm) was connected to the polarization controller (PCD-M02 marked in Fig. 1 as PC). Then, it was terminated with a 10-GHz phase modulator (LN53S-FC marked in Fig. 1 as PM) followed by a silver mirror with a reflectance of 98%@1.550 µm (P1-SMF28ER-P01-1 marked in Fig. 1 as MIR). The mirror (MIR) reflects both pulses propagating in the system in the same way, introducing the constant phase change of 180°. The reflection phase does not affect the system operation because the phase difference between pulses is used to encode information. In such configuration two pulses propagating in the SM fibre (Fig. 1c) were reflected. Taking into account that polarization controller (PC) changed their polarization state (Fig. 1d), the faster pulse went through the longer arm (arm2) and had vertical polarization, while the slower pulse propagated through the shorter arm (arm1) which additionally rotated its polarization from the initial horizontal to the vertical one. Both pulses could interfere at the BS due to the fact, that they both had the same arrival time and vertical polarizations (Fig. 1e). For research purposes, Tektronix P6703B optical probes with the conversion gain 1 V/mW and NEP ≤19 pW/√Hz were used. For the final system, it is possible to optimize the detectors in terms of sensitivity and cost.

Mach-Zehnder interferometer (M-ZI) consisting of two optical fibres as arms (arm1 and arm2) was working only for the returning pulses. The signal was registered only at

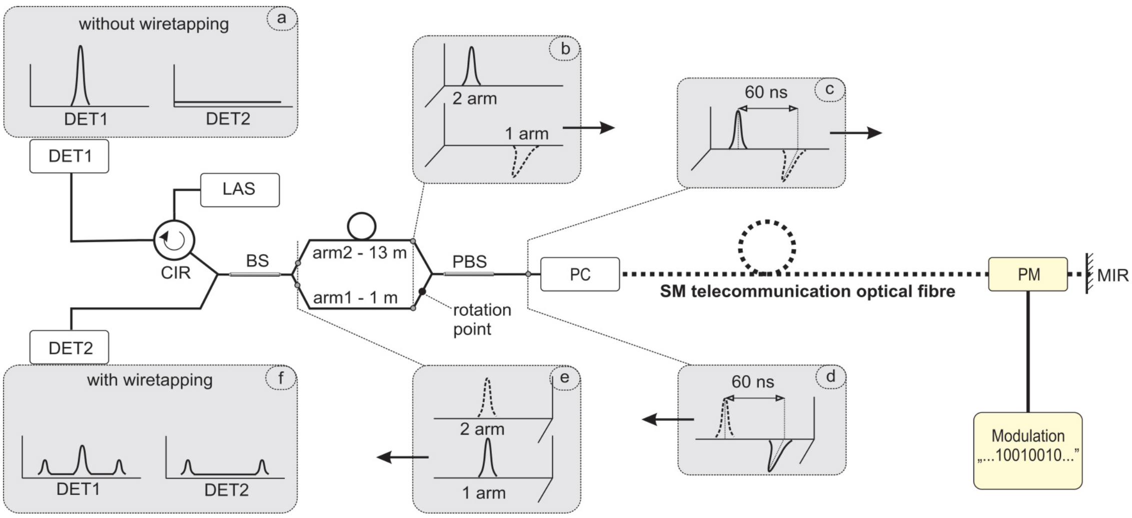

Fig. 1. The scheme of the designed sensor, where DET1 and DET2 are detectors, LAS is the impulsed laser source (1-ns impulse duration time), CIR is the circulator, BS is the beam-splitter, PBS is the polarization beam-splitter, PC denotes the polarisation controler.

one detector DET1 (P6703B marked in Fig. 1 as DET1) in case, when the SM fibre, used for sensing, was not disturbed and, thus, the sensor was ideally stable. This signal was related to the phase-dependent operation of M-ZI. A relatively fast wiretapping-like disturbance was introduced to the sensing fibre and resulted in fast and random changes of polarization of the propagating pulses. The part of the pulses' energy leaked to perpendicular states and, thus, disrupted the interference conditions. Then, the single pulse at DET1 had smaller power and resulted in the appearance of side pulses at both detectors (Fig. 1f). Two-criterion algorithm allowed detection of wiretapping attempts by an independent analysis of both pulses' amplitudes.

It is assumed, that all environmental disturbances uniformly influence pulses and delays because they propagate in the same fibre and disturbances are much slower than separation time between the pulses (60 ns). Although the chromatic dispersion causes the same pulse spreading (from 0.8 ns for a 1-km line to 3.6 ns for a 9-km line - see Fig. 1), it can significantly reduce the system distance and bandwidth.

2.2. *Pulse interferometer as a sensor system*

As described in Ref. 14, the pulse interferometer system has sensor properties. In the case of introduced disturbances during the light propagation in the PC-MIR-PC section, pulse polarization changes may appear. The result of these impulses' interference may take a stochastic form. This is observed on detectors as the signal appearance at DET2 and the signal loss at DET1 channel and, also, as the vanishing of these impulses' interference and the presence of the intensity side fringes (Fig. 1f). All these characteristic features are unlike the steady state of the system operation, when we receive the resulting interference signal only at DET1. The sensing/transmission fibre was naturally exposed to slowly changing fluctuations. Thanks to the PC system, it is possible to continuously adjust the pulse polarization state. A developed measurement algorithm monitors the maximum value of the single interference impulse amplitude at DET1 channel. It must be noted that sensing SM fibre polarization states of the pulses changed during propagation in an unknown way, what was inherently connected with its non-polarization maintaining behaviour. In the case of slow changes' occurrence when the power level of the pulse on DET1 drops down to the determined threshold value, PC system corrects the polarization state in the interferometer.

In the SM optical fibre path, it is also possible to introduce changes in a form of phase disturbances $\Delta\phi$ of radiation propagating in it. These changes can also be caused by mechanical disturbances. Introducing them causes slight changes in the path of propagating radiation and the signal appearance at DET2 in accordance with the following relationships can be observed:

$$I_1(\Delta\phi) = I_0\alpha[1 + V\cos(\Delta\phi)], \quad (1.1a)$$

$$I_2(\Delta\phi) = I_0\alpha[1 - V\cos(\Delta\phi)], \quad (1.1b)$$

where I_0 is the radiation intensity, I_1 is the radiation intensity observed at DET1, I_2 is the radiation intensity observed at DET2, α is the total transmission losses coefficient of the system, V is the visibility of the interference signal expressed by Eq. (1.2):

$$V = \frac{2k_{1s}k_{2s}k_{1t}k_{2t}}{(k_{1s}k_{2s})^2 + (k_{1t}k_{2t})^2}\gamma\cos\eta. \quad (1.2)$$

In Eq. (1.2) k_{ij} are the coupling coefficients for the i-th coupler, the index t is the direct transition (e.g., source - measurement arm), the index s denotes the cross-transition (e.g., source - reference arm), γ is the scalar function of the complex degree of coherence, and 2η is the angle between rays connecting states of fast pulse and slow pulse polarization on the Poincaré sphere.

According to the characteristics of the pulses generated by the radiation source, in the optical fibre path, time separation of the separated on the BS pulses is insignificant. The introduced phase disturbances, forced by means of propagation in the SM fibre, affect both impulses

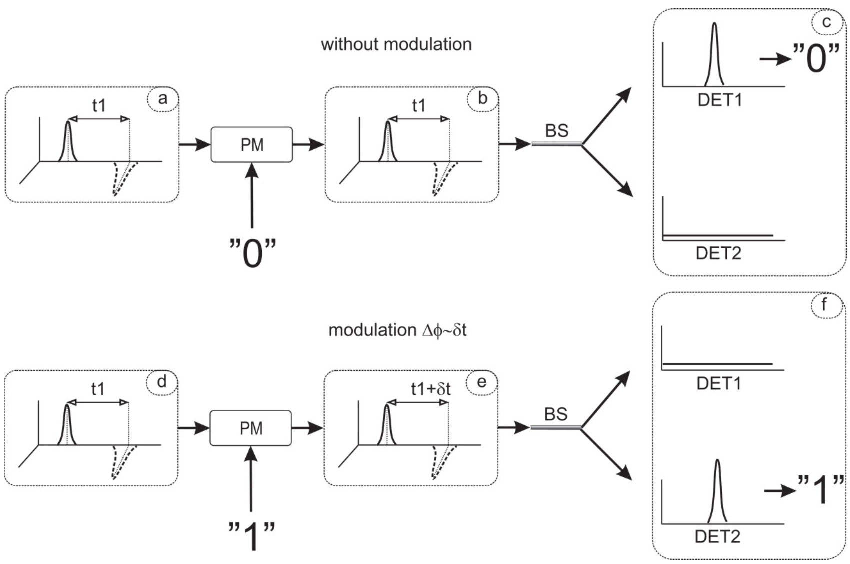

Fig. 2. The scheme of the system with and without intorduced forced phase modulation PM.

almost equally. Therefore, the introduced resulting phase differences $\Delta\varphi$ after joining BS are close to 0.

2.3. Pulse interferometer as a phase coding system

Another situation is presented by the introduction of modulation forced by means of a controlled phase modulator (PM) system by an AFG3022C type generator. This element enables synchronization of the system operation in order to modulate the phase of only one selected pulse along PM-MIR-PM propagation path. Thanks to such a treatment it is possible to control the extent of $\Delta\phi$ changes. According to dependencies 1.1, two values of the introduced forced phase modulation can be distinguished. The system operation states with possible modulation with PM are shown in Fig. 2.

In case when the modulating signal is not introduced by PM $\Delta\phi$=0 the propagating pulses, Fig. 2a, with predefined polarization characteristics are time-separated by t_1, according to the difference of optical paths between the arms (arm1 - arm2). Then, they are reflected from the mirror (MIR) and pass through the BS in accordance with the dependencies 1.1 impinge only DET1. In the case of introducing modulating signal by PM only for the pulse propagating through the arm2, Fig. 2e, an additional delay δt is observed. This delay is tuned so that it is proportional to the resultant phase difference $\Delta\phi=\frac{\pi}{2}$. As a result of such an operation, according to 1.1, the interference result will be observed at DET2, Fig. 2f. The resultant values of the phase differences between impulses that were introduced using PM allow observing pulses' interference on different detectors.

Assigning logical values "0" for $\Delta\phi$=0 and "1" for $\Delta\phi=\frac{\pi}{2}$, respectively, enables transmission of bit information encoded as a phase between PM and two detectors (DET1 and DET2).

The scheme illustrated in Fig. 3 illustrates the idea of the optical phase coding system operation. The modulation characteristics of the PM phase adjuster system is reproducible by means of synchronous registration of signals from DET1 and DET2 detectors by the data acquisition system. In our case, the acquisition system was a P6703B oscilloscope with dedicated algorithms coded in the LabView and Matlab software environments.

3. Experimental setup

3.1. Stability of the system operation

The system (Fig. 1) with a multikilometer long measuring optical fibre line is sensitive to the environmental changes. In order to eliminate all slow changes, a system measuring interference impulses' amplitude and enabling polarization state monitoring was developed. The control algorithms allowed us to correct the system operation in case of slow changes. In the first case, the sensor system was measured in long-term work. Thus, control algorithms were checked and calibrated. Figure 4 presents an example of the system operation results within a period of one day.

The length of the tested telecommunication line was of

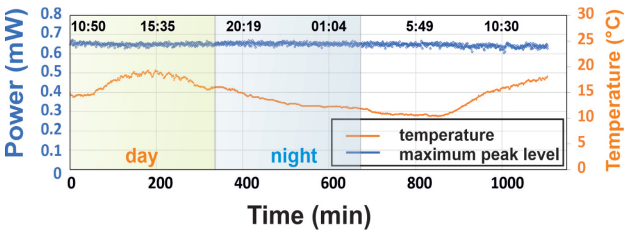

Fig. 4. The exemplary results of long-term testing of system operation

1 km. The impulse interferometer system maintained stable operation at daily temperature changes. The mechanism of polarisation correction was not activated during the whole test.

As a part of the test, some intentional disorders in an SM fibre were also repeatedly performed. Figure 5 shows the moment of the polarization correction system activation. Each attempt to violate the optical fibre and the resultant change in the state of polarization was eliminated to the normal working conditions. The results of the control algorithm operation optimization and many conducted tests indicated that the system response time is Δt=55±10 s. This includes the time needed to develop the optimal PC controller polarity settings. The proposed polarization monitoring/tracking system increases the proposed solution's total cost , but transmitted information security is the priority here, while other costs are usually acceptable.

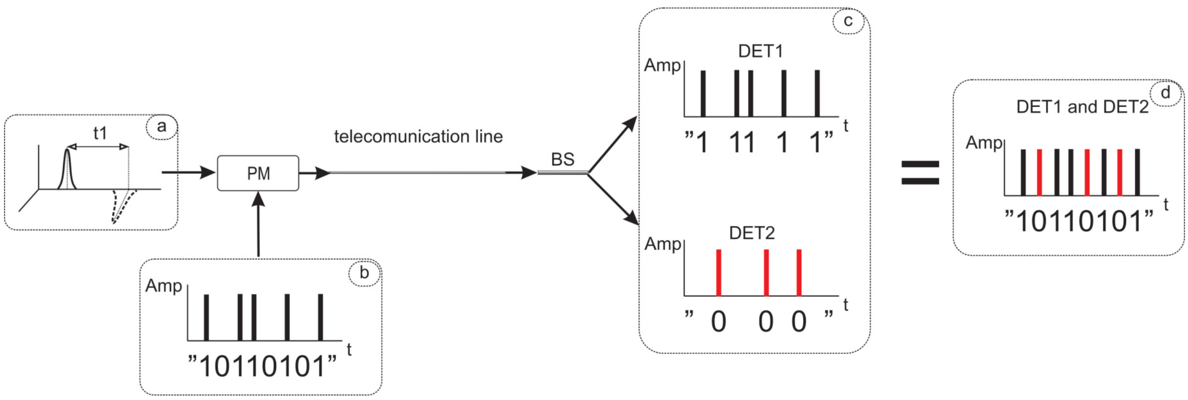

Fig. 3. The scheme of the optical information phase coding system in an optical fibre telecommunication channel

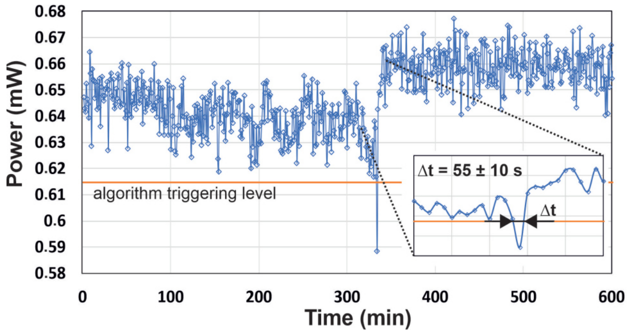

Fig. 5. The exemplary results of long-term testing of the system.

The correct operation of the polarization control system and long-term system tests for SM different lengths were conducted. The measurement results are shown in Fig. 6.

Test conditions included five different SM fibre lengths - 1, 2, 3, 4, 9 km. Tests were carried out during system operation with different fibres within 95 hours, each. Single measurement was taken every minute. The diagram in Fig. 6 presents the average power value calculated from data collected within five hours. Due to the research extensive range, temperature dependence on time only for a 1-km optical fibre was presented in Fig. 6. All optoelectronic systems were located on the laboratory premises under the controlled conditions at a temperature of approximately 26 °C. The optical fibre itself was exposed to changing environmental conditions outside the building. During tests, the ambient temperature of the SM

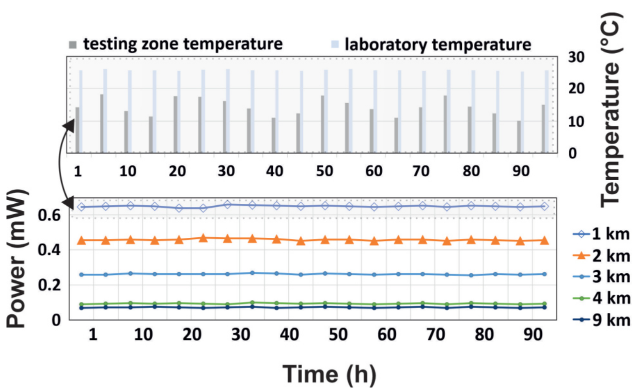

Fig. 6. The exemplary results of long-term testing of system operation for different lenghts of SM.

fibre changed in accordance with the daily cycle in the range of 11-19 °C. It should be noted that in the case of measurements of other SM fibre lengths, the environmental temperature conditions were similar with those presented for the 1-km section. In the results' analysis, the long-term stability of the pulse interferometer system in each of the measured lengths was observed. The decrease of the maximum pulse power at DET1 along with the increase of the SM measuring section length result from the increase of attenuation in the optical path, the excessive number of reflections from optical fibre connectors and the laser pulse broadening. Selected representative measurements of the amplitude and temporal interference impulses are shown in Fig. 7.

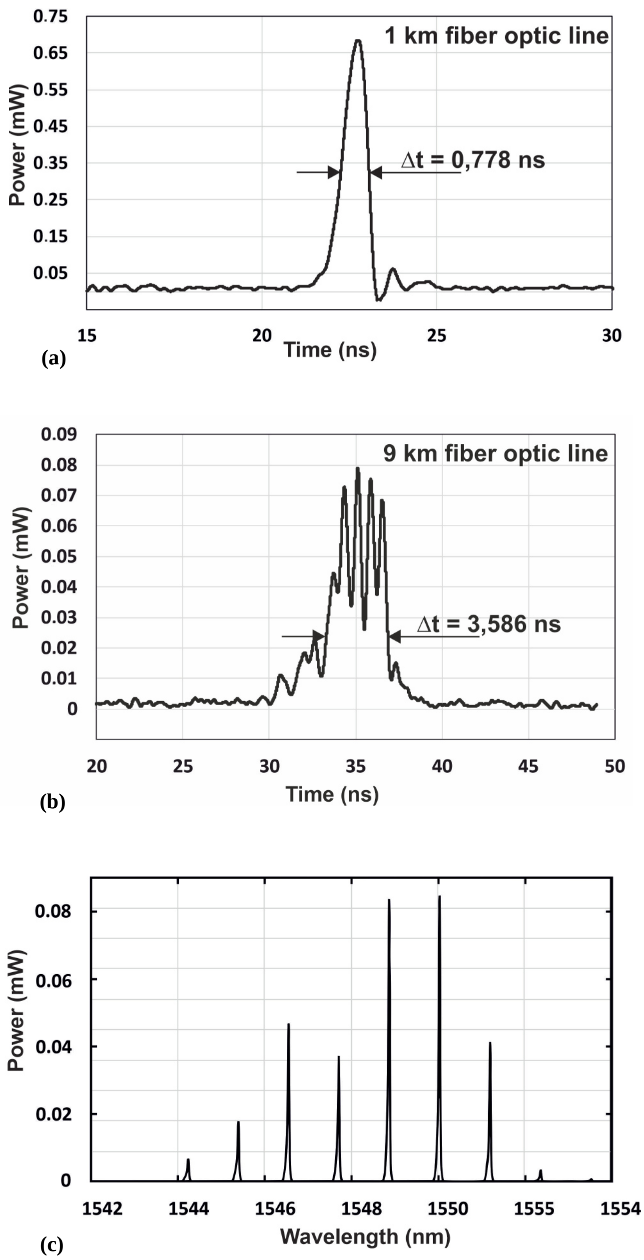

Fig. 7. Interference impulse registered at DET1 during tests of section having the length of 1 km (a) and 9 km (b). For the 9-km optical fibre, the chromatic dispersion associated with the multimode laser spectrum (c) becomes apparent.

It should be pointed out, that in the described system for the 1-km distance of the SM section, the light travels 2 km and 9 km - 18 km, respectively. This results in a decrease of the maximum radiation power at DET1 almost ten times and in broadening of the interference impulse over three-times. For the 9-km optical fibre section, the decrease in pulse power and its temporal broadening result from higher attenuation of the optical fibre path (two additional connectors and 8 km of the optical fibre) and the dispersion in the optical fibre. A 9-km fibre with the double pass results in the optical path of 18 km, and optical path duplication also duplicates transmission losses and dispersion effects. These changes did not affect, in the analyzed cases, the correct and stable operation of the system which is illustrated in Fig. 6. The fact that the length of the SM section limits the operating range of the phase coding system is a different topic.

3.2. System measurements in the phase coding range

For each of the analyzed cases of SM optical fibre different lengths, the correctness of the bit exchange by coding them using phase modulation of the interfering impulses was tested. According to telecommunication standards, the required value of test duration was determined in order to calculate the bit error rate (BER). The PM element was stochastically modulated with a series of triggering pulses [Fig. 8(a)] with a given voltage and time characteristics for each SM length. Then, on the detectors DET1 and DET2 [Figs. 8(b) and 8(c)] interference impulses were synchronously recorded and counted.

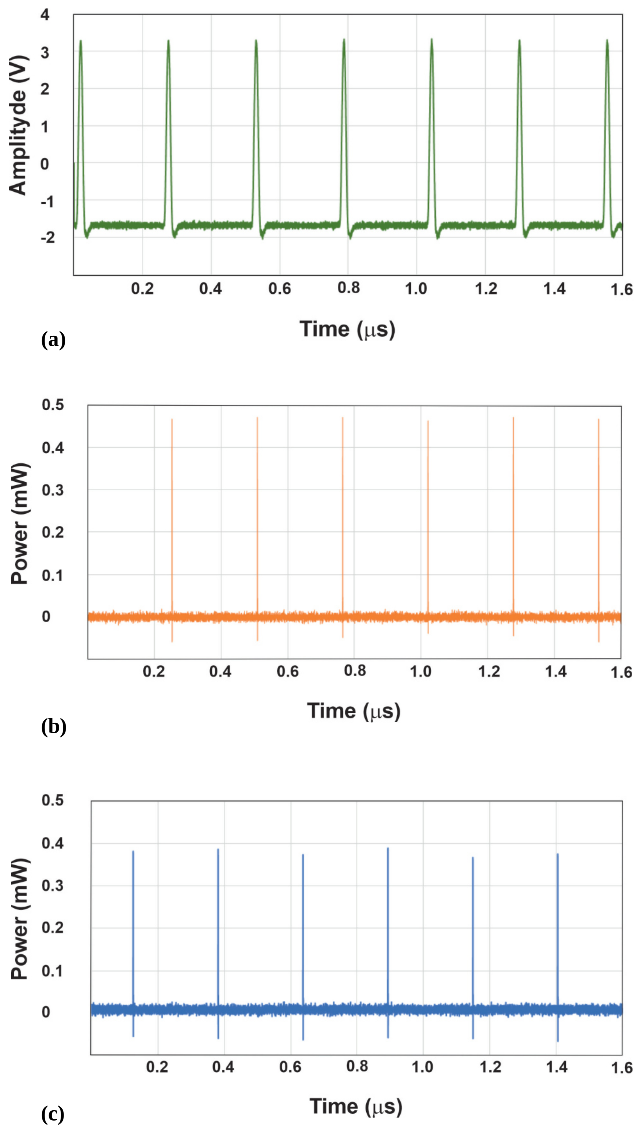

Fig. 8. Exemplary time characteristics of series of pulses controlling phase modulator PM (a), and recorded interference impulses on DET1 (b) and DET2 (c), respectively.

A particular number of errors in a given unit of measurement duration for a given length of the optical fibre has made it possible to determine the BER coefficient for each case of the PM modulation frequency. Table 1 summarizes the system's test results. BER measurement is carried out by sending a specific number of bits, hence the decrease in the bit rate will increase the time required for the transmission of the required number of bits.

Table 1: BER values of the tested system.

Measurement time [s]	Bit rate [Mbit/s]	BER (Bit Error Rate)			
		Length of the measuring fiber			
		1 km	2 km	4 km	9 km
2303	10	$1.1\ 10^{-11}$	$1.6\ 10^{-11}$	$2.1\ 10^{-11}$	$7.8\ 10^{-11}$
921	25	$1.2\ 10^{-11}$	$1.5\ 10^{-11}$	$2.2\ 10^{-11}$	$8\ 10^{-11}$
460	50	$1.1\ 10^{-11}$	$1.4\ 10^{-11}$	$2.3\ 10^{-11}$	$8.2\ 10^{-11}$
360	64	$1.2\ 10^{-11}$	$1.6\ 10^{-11}$	$2.1\ 10^{-11}$	$9.1\ 10^{-11}$
230	100	$1.2\ 10^{-11}$	$1.5\ 10^{-11}$	$2.1\ 10^{-11}$	$8\ 10^{-11}$
184	125	$1.3\ 10^{-11}$	$1.5\ 10^{-11}$	$2.2\ 10^{-11}$	$7.9\ 10^{-11}$

Measured: at 25°C - laboratory, at 18°C - fiber optic test field.

Table 1 indicates that the system allows encoding information in the optical physical layer of the telecommunication channel with working parameters consistent with telecommunication STM-1 regulatory requirements. Bearing in mind that the system uses phase coding of light, it should be stated that it is possible to develop a new type of the secure information transmission system. This type of system may have much better parameters (bit rate in the range of 100 Mbit/s) in the transmission of the code key than the current QKD systems. The safety of the setup is guaranteed by the need to restore the generation-detection system. The authors assume that in order to read the information, it is necessary to obtain 90% certainty of the correct reading of the eavesdropped information

In order to eavesdrop on the transmission, due to the coding of the information by means of the phase difference between two pulses separated in time and polarization, it is necessary to obtain interference of pulses carrying information. The best method is to duplicate the system which generates and detects pulses and next decoupling the radiation from the transmission path to the eavesdropping system, where the pulses can interfere. There are three stages of matching the eavesdropping system:

1. Obtaining interference of the corresponding parts of the pulses generated by the setup requires adjusting the setup imbalance in accordance with the pulse duration. Assuming the duration of the pulse of ti = 1 ns, the image must be reproduced to the nearest 20 mm.
2. Obtaining the corresponding interference and correct reading of the information encoded in the phase requires adjusting the radiation optical path in accordance with the used wavelength of radiation. When using a laser with a wavelength λ = 1550 nm, the imbalance must be reproduced with an accuracy of 155 nm. The imbalance allowing reliable reading of the encoded information was assumed as 10% of the laser wavelength (1550 nm), i.e., 155 nm. In theory, one can also assume a higher value (e.g., 25%), but the probability of a correct reading decreases as the imbalance increases.
3. Despite the exact reproduction of the layout, it is still necessary to match the polarization of the "eavesdropped" radiation to the polarizing beam splitter so that the corresponding pulses interfere with each other. Due to the stochastic, unpredictable polarization state of radiation in the single-mode telecommunications' fibre and the use of the transmission setup as a sensor, assuming a 9-km line, the eavesdropper will have a time of single

milliseconds to match and read the transmitted information. 50 µs is the time of reaching the pulse to the detector, about 2 ms is the time of alarm signal generation and transmission stop.

A 1-ns pulse duration is sufficient to provide the 100 Mbit bandwidth. To increase the bandwidth, it is necessary to shorten the pulse duration or use WDM techniques which can significantly increase the cost of the system. However, high bandwidth is usually not required because the amount of transferred data is small (encrypted text data). It should be also underlined that in the considered system the security of transmitted information is the priority, while other costs are usually acceptable.

4. Conclusions

In the article, the authors show that it is possible to send encoded information using a phase state in the Mach-Zehnder pulse interferometer. The system retains sensor properties. Data exchange security is based on the need to eavesdrop of optical transmission channel with the precise mapping generation setup, as well as matching the detection to stochastic polarization changes. Bit rate errors for the system achieved during the research are competitive in relation to other methods of data protection in fibre optics. Bearing in mind the above factors, the authors know that it is possible to eavesdrop on this setup, however, the sensor's character of the setup provides detection of wiretapping attempts and protection of transmitted information.

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