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Power supply of military fiber-optic temperature and strain sensors using the polarization-division multiplexing

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The article proves the possibility of using polarization-division multiplexing to power-supply temperature and strain fiber-optic polarization sensors, along with maintaining their high sensitivity to measured quantities. The main advantages of sensors are their light weight, reliability, wide field of sensing and absence of electricity, which make them suitable for use in environments with a high possibility of an explosion. Polarization-division multiplexing increases the capacity of already existing single-mode routes and allows simultaneous power supplying of the sensor and data transmission on one wavelength. The article describes the development of a bidirectional sensor utilizing a polarization beam splitter, which is independent of the polarization state, thereby increasing its reliability and sensitivity to measured quantities. The high sensitivity and stability of the bidirectional sensor in measuring temperature and strain changes are confirmed by mathematical descriptions of the ongoing phenomena. The two-way, one-fiber sensor, which is based on a polarization beam splitter, represents an ideal solution due to its polarization independence. This type of sensor was tested for changes in temperature, pressure, tension, and deformation.

Keywords: multiplexing, polarization, temperature sensor, strain sensor, remote power supply.

1. Introduction

Polarization-division multiplexing enables simultaneous data transmission and sensor power supply over a single mode silica-based optical fiber (G.652), which is particularly advantageous for distributed sensing in hazardous environments. Fiber-optic polarization sensors, especially those utilizing PANDA fibers, offer high sensitivity and immunity to electromagnetic interference. The integration of a polarization beam splitter further enhances the system's reliability by ensuring polarization independence. Finally, the concept of remote power supply is crucial for deploying sensors in locations where electrical power is either unavailable or undesirable due to safety concerns. These technologies collectively form the foundation of the sensor system presented in this paper. The article describes the development of a bidirectional sensor utilizing a polarization beam splitter, which is independent of the polarization state, thus increasing its reliability and sensitivity to measured quantities such as temperature and deformation changes. Experimental results confirm the high sensitivity and stability of the bidirectional sensor in measuring temperature and deformation changes. Due to their special properties, they can also be used as a part of sensor systems [1]. It is possible to divide sensors into two main categories according to the type of fiber utilized as the sensor. The first are extrinsic sensors, where the fiber only plays the role of power-supplying, or signal transmission from the measuring device. The second type are intrinsic sensors, where the sensing part is the fiber itself [2]. This includes Bragg grating sensors, interferometry-based sensors and especially polarization sensors, which are the basic theme of this article thesis. Given that polarization fiber sensors, Bragg gratings, and other interferometric sensors are very similar in their design and compete with each other, we consider it necessary to compare these types of sensors side by side to clearly highlight their advantages and disadvantages.

Bragg grating sensors are widespread and have a variety of applications in sensing temperature, strain, pressure, and many others. The sensor itself is created by a grating pattern inside the fiber. This periodical pattern has a different refractive index that causes it to reflect a certain wavelength back according to the external change. Only the sensing parts contain the grating pattern; thus, the rest of fiber, without gratings, is not sensitive to external changes. References [3,4] contain a description of different types of gratings, manufacturing and provide a comprehensive overview. The sensing principle remains the same, but for temperature sensing, it is primarily focused on different types of encapsulation techniques, such as tubulate, substrate and metal research, as described in [5]. Metal encapsulation [6] allows a rapid increase of the sensor's sensitivity and response time. This type is also widely used in measuring low and extremely low temperature values, ranging from 0 to 400 K, due to the mounting of the sensing part on a polytetrafluoroethylene coupon [7]. High temperature values can also be measured with the gas packing method [8].

Interferometry based sensors also belong to one of the most important sensor types. They have high sensitivity and accuracy, and are capable of sensing many quantities in detail, such as temperature, pressure and others, as described in [9,10]. The basic operating principle is based on the signal interference after a change in the measured environment. Common types of interferometers are the Mach–Zehnder, Michelson, Fabry–Perot [11,12], and Sagnac. The vibration sensor described in [13] is based on asymmetric dual Mach–Zehnder interferometry. The operating wavelengths are close to 1550 nm and the sensor utilizes wavelength division multiplexing in order to suppress the signal-to-noise ratio. Temperature measuring can be found in [14], where the sensor is proposed and subsequently tested and modified for sensing in a wide range. A system using a thin core fiber interferometer described in [15] is capable of sensing up to 850 °C. [16] compares the interferometry-based sensing systems and polarization sensing systems for acoustic vibrations in order to explore the exposed length of possible digging on an optical route.

Research on polarization sensors has significantly advanced in recent years, especially in the field of optical fibers, which enable the measurement of non-electrical quantities such as temperature, pressure, and other physical quantities. These sensors are capable of distributed measurement along the entire length of the fiber, which is advantageous for monitoring large objects or environments with explosion risks [17,18]. As a result, they find applications in military security of objects, robotics, or extreme conditions where electrical power is not available [19-21]. Research teams are also focusing on increasing the sensitivity of sensors using elliptical cores or photonic crystal structures [22-24].

This paper focuses on the extrinsic type of sensor and the distributed fiber-optic polarization sensor, which consists of a polarization-maintaining and dispersion-compensating fiber abbreviated as PANDA. The ability of the stress rods to induce artificial birefringence and spread the coming optical signal into two channels (in the y and x polarization planes), based on different spreading velocities allow them to react to the temperature changes as well [25]. There are many approaches and measurements for using a single mode fiber and its properties [26-28] because it is able to detect changes in an already existing optical route. However, single mode fiber sensing properties are not supported by the stress rods, as in the case of the polarization maintaining fiber. Many articles support the variability and the large possibilities of practical utilization of polarization for sensing purposes across the scientific fields [29-33]. This supports the importance and suitability of the sensor itself.

The fiber-optic polarization sensor is a lightweight, non-electrical sensor that is suitable for placing in dangerous environments. Sensors designed for gas tanks [34], industrial equipment, biochemical applications [35], military ammunition storage, or the petrochemical industry require specific sensor requirements and must be free of electrical charge due to the risk of explosion. To ensure sufficient sensitivity, it is necessary to have light with a clearly defined polarization state at the input [36].

For sensing temperature, researchers in [37] used a solid photonic fiber crystal core instead of a polarization maintaining fiber. In this case, there is a different principle of wave guiding. Into the holes in solid core photonic fiber crystal were put the oil and there is proposed and theoretically proven to utilization of a new sensor type. The proposed sensor is subsequently exposed and tested to temperatures of 20, 40, 60 and 80 °C with plotted spectrum and a peak around 1550 nm. Polarization plays an important role, but there is a polarization-independent absorber described in [38] for collecting solar energy. [39] are based on the plasmonic principle, where the interaction between the plasmons changes the refractive indices resulting in the possibility of measuring temperature, humidity, and strain. However, this technology is based on the manipulation of structural parameters, which come with its own challenges. Therefore, using only one manufactured polarization maintaining fiber has its advantages.

2. Theoretical basis and methods

The polarization sensor applications presented in this paper use polarization maintaining and absorption reduction fibers, abbreviated as PANDA. Their special property is birefringence. Artificial birefringence is induced in these fibers by introducing regions of different thermal expansion into the cladding. These regions cause mechanical stress on the fiber core and thus birefringence. Birefringence can be characterized in a fiber by two linear polarization modes that propagate during excitation in two orthogonal axes, the fast axis and the slow axis [25]. The origins of birefringence, such as mechanical stress on the fiber core and the thermal expansion of the stress regions, led to the idea of using these fibers as temperature (absorbed heat) and mechanical deformation sensors.

The fundamental principle involves the simultaneous excitation of two polarization modes, which propagate at different velocities depending on absorbed heat or mechanical deformation. This velocity difference produces a phase shift that is evaluated at the fiber output. In practice, achieving perfectly equal excitation of both axes can be challenging. Unequal power distribution or even degradation to elliptical polarization may occur, particularly when the sensor is located far from the source and the evaluation unit, and the optical wave travels through a single-mode fiber, such as a telecommunications cable. In this case, sensor development has moved towards more complex variants of two-fiber arrangements or arrangements where the sensor fiber is excited from both directions. This arrangement (one-fiber two-way) is used in the following experiments, only Section 3.1 contains the description of temperature changes measured by the one-way sensor so that the historical context is complete.

3. Experimental results

3.1. Temperature changes measured by one-way sensor

As indicated, it is first necessary to carry out the temperature changes measured by one-way sensor. These results are described in detail in [25]. Thanks to the outcomes of this measurement, it will be possible to demonstrate the differences between the one-way and two-way sensor (Fig. 1). The fiber-optic polarization sensor's sensitivity was tested by applying a container of water at different temperatures (0 and 48 °C). The temperature in the laboratory was constantly 24 °C. Measurements lasted 120 seconds, the polarimeter and laser power meter had a sampling period of one second. Container application is a method focused on the sensor's reaction to a temperature change.

Thermal radiation from the applied container influences the transmitting properties of the fiber. Temperature change measurement plays a vital role in testing the sensor.

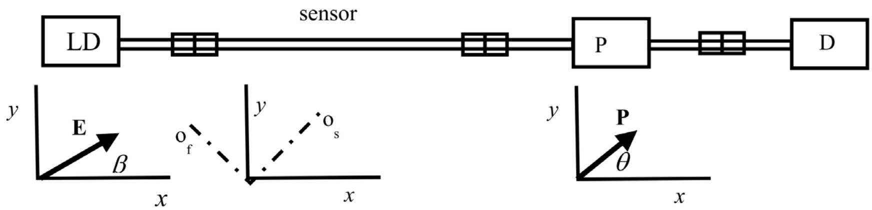

Fig. 1. The model of one-way one-fiber sensor [25]. LD – laser diode, P – linear in-line polarizer, and D – photodiode.

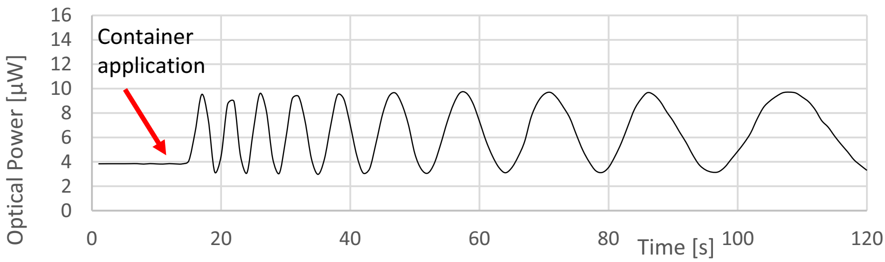

Fig. 2. Sensor power response to the applied container of water 0 °C (crushed ice).

In Fig. 2 the sensor exhibits an immediate reaction upon reaching the maximum value of around 10 μW, followed by a harmonious course with almost the same period. This output power was measured by a laser power meter and is composed of a purely linear vertical polarization state because of the connected linear polarizer.

But the exact phase shift δ depends on the value of temperature coefficient of the effective refractive index α calculated as

$$\delta = \frac{2\pi}{\lambda} l \alpha \Delta \vartheta = \frac{2\pi}{1550 \times 10^{-9}} 2\alpha(48 - 24) = 61.93 \times 10^{6} \alpha \pi \quad (1)$$

where l is length of fiber, $\Delta\vartheta$ refers to the change in temperature and 61.93×10^6 is the result of multiplying constants. 2π corresponds to the full angle of a circle in radians. In the case of two times longer fiber which was the sensor 2 is the result captured in (2).

$$\delta = \frac{2\pi}{\lambda} l \alpha \Delta \vartheta = \frac{2\pi}{1550 \times 10^{-9}} 4\alpha(0 - 24) = -123.87 \times 10^{6} \alpha \pi \quad (2)$$

3.2. Temperature reaction in two-way polarization independent sensor

A one-way variant of the sensor was used in this measurement. The advantage is the possibility of measuring with only a single fiber. However, the connection requires a high-quality and defined state of polarization at the input so that when light passes through a rotated +45° connector, both axes are evenly excited and the changes in birefringence are reflected. Power-supplying with a single-mode route, which does not preserve polarization, leads to degradation of the polarization state during transmission. Subsequently, the polarization beam splitter does not distribute the beams evenly, but rather one branch has more energy compared to the other, which has a negative effect on the sensitivity of the sensor itself. In extreme cases, only one branch could work. This problem can be solved by using a polarization divider and circulator in a one-fiber – two-way variant. Polarization appeared to be independent so we do not longer consider connection from Fig. 1.

For the one-fiber two-way variant from Fig. 3, it was typical to connect a polarization splitter (P/N: PBC-1X2-P-1550-900-3-1-FC), which divides the input polarization into two branches: E_x and E_y and the polarization independent circulator (P/N: CIRC-SM-55-FC-ABS-1m-d2mm). The individual intensities pass through the same part of the sensor and at the end, they were again combined using a polarizing splitter, which also acted as a combiner. Sensor testing lasted 920 s, with the time of application of 140th second. The ambient temperature was 24 °C and the metal container of water with melting ice is applied at 140 s. Thermal radiation after application causes immediate power response. Measurements and detailed physical principles can be found [40, 41]. The advantage was that the sensitivity was not affected by any polarization state, because the passage of total light with the desired properties will always be ensured. The properties of a three-arm optical circulator were used for signal evaluation and processing. A polarization-independent optical circulator was used, which

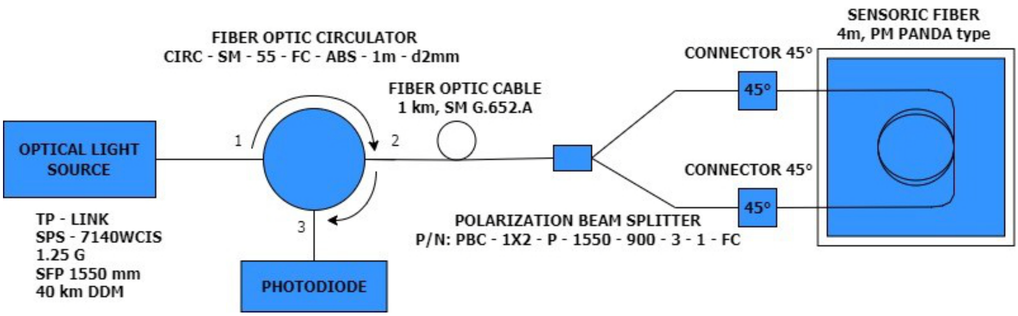

Fig. 3. Two-way one-fiber sensor arrangement of workplace for measuring thermal dependencies.

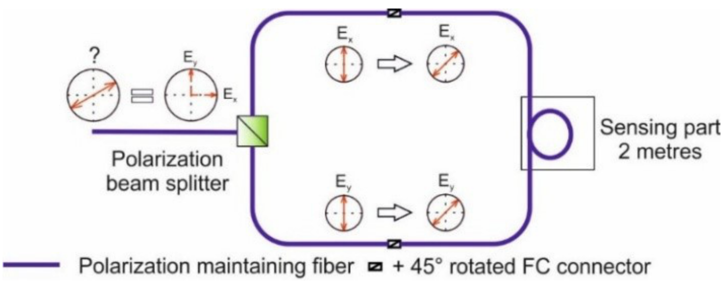

Fig. 4. Two-way one-fiber sensor arrangement based on the polarization beam splitter principle.

is made of a classic single mode fiber, so any polarization could appear at the input of the polarization splitter, as shown in Fig. 4.

During the testing of set-up from Figs. 3 and 4, the original two-arm and double -threaded arrangements were replaced in each sensor with a circulator evaluated by a laser power meter VEGA. This type can be connected and combined in various ways depending on the required length of the monitored space.

There is the mathematical description of phase shift more complex because we need to consider the influence of both ways and sum them at the end of sensor in circulator. Due to the same length it is convenient to use the same equation (3). But multiply the result by coefficient 2.

$$\delta = \frac{2\pi}{\lambda} l \alpha \Delta \vartheta = \frac{2\pi}{1550 \times 10^{-9}} (2 \cdot 2) \alpha (0 - 24) = -123.87 \times 10^{6} \alpha \pi \qquad (3)$$

According to the results it is possible to assume that in only 2 meters long fiber is caused the same phase shift.

3.3. Measurement tensile dependences

The workplace for measuring tensile dependencies was connected according to Fig. 4. The optical source SFP-DWDM-120km-1Gbps-CIS-34 was used to simulate real routes and real sources from telecommunications with the possibility of using wavelength multiplexing. A 4 m long PANDA sensor fiber was attached to the Prooftester Tensile testing device manufactured by NetworkGroup.

The measurements were carried out cyclically with a period of 20 s (stretching –releasing the fiber). One period is shown in Fig. 6. At 803 s, the stretching of the filament started. At 810 seconds, the required force was reached. The twitching noticeable in the next 10 seconds was caused by the slippage of the filament at the point of its attachment and the automatic tension adjustment to the value of 15 N. At 820 s, the filament was suddenly released. The rotation frequency of the optical power meter was 16 Hz.

Measurements were made for an applied force ranging from 1 to 20 N. When more force was applied, the fiber broke. To try to calibrate the sensor for accurate tensile

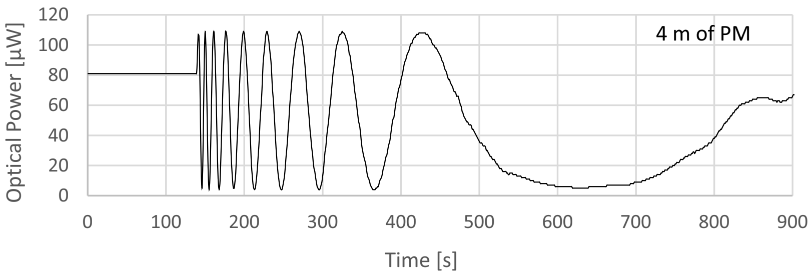

Fig. 5. Two-way one-fiber sensor functional test of a sensor based on a polarization splitter and an optical circulator and 4 m of PM sensor (Measurement 401).

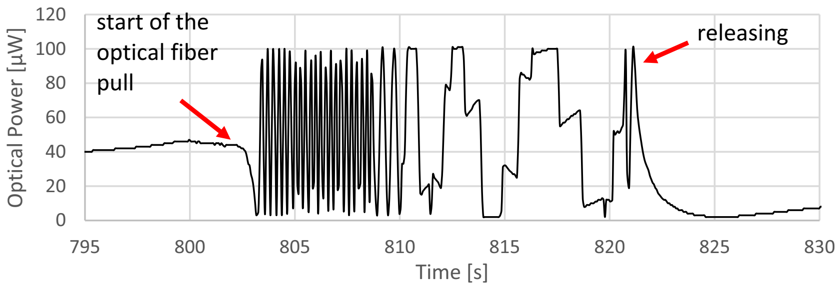

Fig. 6. Two-way one-fiber sensor reaction of the sensor when stretching the fiber with force $F = 15$ N (Measurement 0437).

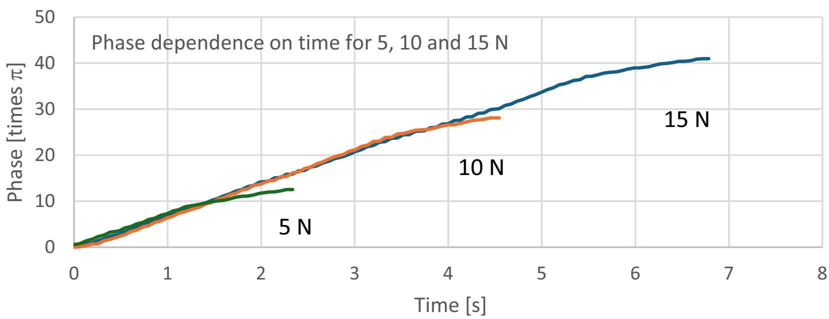

Fig. 7. Interpretation of the total change in optical power or recalculated phase.

measurements, Fig. 7 was created by mathematically integrating the total change in optical power converted to phase changes. It shows a linear relationship between the applied force and the phase change which can be interpreted as sensor sensitivity. Given the fact that these measurements were repeatedly performed to ensure statistical deviation, the visible trend directive can be considered accurate.

4. Discussion

The use of polarization-division multiplexing has proven to be an effective method for extending the application of existing optical paths. Thanks to the testing performed, this option was shown to be suitable for the purpose of powering fiber optic polarization temperature sensors (Fig. 3). Temperature changes were measured by applying a container at 0 and 48 °C in a laboratory environment at 24 °C. The measurement was evaluated with the help of a polarimeter, which was able to capture and process multiple properties of light. Follow-up tests were carried out with a connected linear polarizer and optical power meter. The optical power meter can measure incident optical power, where the individual components of the incident light can no longer be distinguished, but for real applications, it seems to be an ideal choice due to simplicity and affordability. The wiring according to Fig. 3 was dependent on the state of polarization after passing through the single-mode optical fiber G.652, which does not preserve polarization. This could affect the resulting sensitivity of both sensory branches, so the arrangement was changed according to Fig. 4 for further testing. Here, instead of the connected tear-off, an optical fiber in a polystyrene box was utilized to prevent distortion of the results due to the surrounding environment.

All the measured results and graphs presented here confirmed that the variant of the sensor arrangement using a single fiber two-way (two-way one-fiber) is also usable with advantages as a remote power supply. In particular, Figs. 5, 6 and 7 are clear evidence that this type of sensor is also suitable for sensors tens of kilometers away, which was verified not only in laboratory conditions, but also on real optical routes of the Brno Experimental Academic Optical Network (BEAON) and the military training facilities in Boletice and Březina.

The advantage of the sensor described and designed here is the possibility of remote light supply. If the presence of a power supply in the vicinity of the sensor is acceptable, the same excitation of both polarization axes is no problem – it is possible to use excitation by linear polarization at an angle $\pi/4$ to the polarization axes directly at the location of the sensor. In experiments, an instrument for measuring the time difference in the propagation of polarization modes (PMD analyzer) was used for calibration of the sensor. Thus, it was possible to determine the sensitivity per unit of length and unit of tension. However, it is not possible to use time difference gauges in a real sensor due to price and system compatibility. Usually, this type of sensor is utilized with remote light supply to take advantage of the physical principle of light propagation. In these cases, the time difference in the propagation of polarization modes can be expressed in terms of the phase difference. Measuring the phase difference brings some problems, likely solvable by electronics with memory. Unlike a thermal sensor, where the result is a change (arbitrary) in the phase difference on heat exposure, a pressure sensor will need to measure the absolute value of the change in phase difference. The evaluation of the electrical signal on the photodiode is then a matter of advanced signal processing.

The proposed sensor is classified as a relative sensor, *i.e.*, it evaluates relative changes in the measured quantity. This evaluation can be twofold. The result is the information that the monitored variable has changed, *i.e.*, the given state has been disturbed. An example is the disruption of the temperature field by the presence of a foreign object or the disruption of the compactness of the object. Similarly, in the case of a deformation sensor, the information can indicate a disturbance, for example, by the passage of a vehicle. The second, more interesting variant of the relative sensor is a sensor that records the change of the monitored variable with respect to the equilibrium or steady state. Here, its properties are close to those of an absolute sensor without recording the continuous values of the measured variable. Table 1 highlights the advantages of both variants of the sensor arrangement. Thus far, research and experiments confirm the possibilities of using different types of sensors for different applications.

Temperature hysteresis plays an important role because it is described in temperature difference. In the case of the different ambient temperature, the overall difference can be smaller so it results in the smaller signal response. Nevertheless, this can be

Table 1. Table of comparison one- and two-way sensor type.

	Two-way	One-way
Polarization independence	Yes	No
Power-supplying	Any type	Additional components necessary (linear polarizer)
Sensitivity	Maximum	In some
Temperature detection	Measured	Measured
Temperature range	0–48 °C	0–48 °C
Tensile detection	Measured	Measured
Tensile range	5, 10, 15 N	5, 10, 15 N
Cylindrical usage	Possible (included)	Possible

also transformed into an advantage, when it is important to have maximum sensitivity in a slightly changing environment.

In general, temperature hysteresis is a phenomenon where the sensor's response depends not only on the current temperature but also on the previous thermal state. This means that during heating and cooling, the sensor does not behave exactly the same—the curves show a certain deviation. In our case, hysteresis is partially included during the measurement to external change when the surroundings of the sensor itself create new ambient temperature after some time. This is supported by reaching a new polarization state and after the removing the container polarization state changes to the initial state.

Particularly from Fig. 7, it is evident, given the repeated measurements and the analysis of the measured data, that there are certain limitations and disadvantages of the presented sensor technology, which mainly lie in the flexibility and strength of the optical fiber used. The measurement range is therefore always slightly smaller than the defined strength, and we can talk about an accuracy of approximately 95%, as indicated by the measured values. The slight imperfections in the measured curves are more likely caused by the imperfect measuring device, which was custom-made for our measurements in the military laboratories of the University of Defense.

Given the military applications and the effort to eliminate the need for electricity in explosive environments, it is necessary to conduct a cost-benefit analysis compared to traditional electronic sensors in terms of CAPEX/OPEX and deployment time. This analysis includes evaluating how the complexity of the sensor and its deployment affect the overall costs and time required for implementation. Furthermore, it is essential to discuss the standardization paths of ITU-T G-series for telecommunication fibers and MIL-STD for integration into defense systems.

5. Contributions, novelty, and research gap

This article offers several significant contributions to the field of fiber-optic sensors, particularly in the context of military and industrial applications. The article demonstrates the possibility of polarization-division multiplexing to power fiber-optic sensors, enabling simultaneous data transmission and sensor power supply without negatively affecting their sensitivity. This approach is particularly suitable for environments with a high risk of explosion, where eliminating electrical power is essential. The article describes the development of a two-way sensor that utilizes a polarization beam splitter. This sensor is independent of the polarization state, enhancing its reliability and sensitivity to measured quantities such as temperature and strain changes. The experimental results confirm the high sensitivity and stability of the two-way sensor in measuring temperature and strain changes. The data are supported by mathematical descriptions of ongoing phenomena, providing deeper insights into the physical principles of sensor operation.

Future research should also explore the integration of these sensors into existing optical networks and their use in different industrial and military environments. Compared to other types of fiber optic sensors, this research shows that polarization sensors represent a new generation of economically more attractive sensors. These sensors enable the creation of extensive addressed networks, and cooperation on existing optical routes.

6. Contributions

Fiber optic polarization sensors have a wide range of applications today. Due to their low weight, resistance to the external environment, non-electrical nature, high sensitivity to the measured quantity, and their low price, they can be placed in environments with a risk of explosion, such as gas exchangers, chemical storage or security systems of military facilities. With this wide range of applications, the requirements for the power supply of the sensors themselves are also increasing. It is assumed that classical single-mode telecommunications G.652 fibers will be used over a common optical path. Another goal of this work was to expand the potential to use a single wavelength for simultaneous data transmission and power supply. This was achieved with the help of polarization-division multiplexing, where a second sensory branch was connected to the arm to test the data transmission. However, the use of SM fiber, which does not maintain polarization, degrades the polarization state, which can result in insufficient sensitivity of the sensor or, in the worst case, its functionality. This negative phenomenon can be suppressed by adding other polarization dynamic control components, which increases the attenuation and financial costs. For this reason, a one-fiber two -way variant of the sensor was designed and successfully tested, which was polarization-independent and completely suppressed the dependence of this sensor on the input polarization and thus the effect on the supply optical fibers. This variant is based on a combination of a polarization divider and a circulator. After passing through the optical path, the polarization state is divided into two components that pass through the fiber. Then they are merged again by the splitter, which in this case behaves as a combiner. The data is then transferred through the circulator to the evaluation element. This can be a polarimeter or a laser power meter. In this paper, an optical power meter was used as an evaluation device, and a sampling rate of 16 samples per second was used for scanning. The polarization sensor was evaluated for its ability to sense temperature (absorbed heat) and mechanical deformation. Temperature testing was carried out by applying containers with water of different temperatures. Mechanical stress testing was carried out in two ways. In one case, by longitudinal stress on the optical fibre ripper, in the other case, by mediated deformation via winding of the optical fiber on the deformation roller, mediating the effect of compressive force. For both temperature detection and mechanical stress, the suitability of the proposed sensor's use and application in various situations was demonstrated.

The possibility of remote power supply of the sensors was verified using the Brno Experimental Academic Optical Network (BEAON) and the military training facilities in Boletice and Březina. This possibility enables not only sensor coverage of remote spaces, but also the implementation of distributed sensors using polarization principles.

Thanks to its independence from input polarization, the one-fiber two-way sensor provides a wide range of research possibilities and applications in various situations.

The research team perceives the greatest limitation or weakness, and at the same time the greatest potential for further research, in the processing of the electrical signal behind the photodiode. Here, the use of modern advanced methods such as artificial intelligence, machine learning, and further analysis is suggested, which, however, must be addressed in connection with the specific application. Therefore, in collaboration with the armed forces of the Czech Republic, the following research is heading in this direction.

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