The Usability Analysis of Different Standard Single-Mode Optical Fibers and Its Installation Methods for the Interferometric Measurements

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Abstract. *With optical fibers we are able to measure a variety of physical quantities. Optical fiber sensors sensitive to the change of the light phase, so-called interferometers referred in this article are one of the most sensitive sensors. Because we are able to detect phase changes with extreme precision, these sensors are thus suitable for demanding applications, where cost is not the main requirement. We have used the Mach-Zehnder configuration. The paper deals with the usage of different types of standard single-mode optical fibers in the civil engineering as an integrated acoustic sensor. Further experiments are focused on the different types of fiber installation methods, such as placement in the mounting foam, into the polystyrene or attachment onto the wooden surface and their effect on the measurements. Through the repeated measurements of harmonic frequencies were obtained information about the usable frequency range and sensitivity of the particular arrangement. Measurement was performed for both cases, where the specific type of fiber or specifically installed fiber was used as the measurement or as the reference. The final evaluation is based both on the experience gained during measurements and also using the statistical calculations.*

Keywords

Different singlemode optical fiber standards, fiber installation methods, fiber optic sensor, Mach–Zehnder interferometer.

1. Introduction

Development of fiber optics communication systems experiences slight stagnation at this time. In contrast, the use of optical components for sensor applications can be considered a region not yet fully explored. We can consider two basic groups of fiber-optic sensors based on the evaluation of light intensity or phase of the light. Sensors evaluating light intensity are generally used for measurement of displacement and other physical phenomena affecting the fiber. On the other hand phase sensors compare the phase of the light between the two beams. These sensors called interferometers are composed of measuring and reference arm. Ideally, the measured phenomenon should not affect the reference arm and should affect only the measuring arm. Phase sensors are more sensitive and more accurate than intensity sensors but their structure is more complicated, technically more demanding and expensive. Nowadays we find their use rather in special applications [1]. The basic types of interferometers are Mach-Zehnder, Fabry-Perot, Sagnac and Michelson. This paper uses the Mach-Zehnder configuration.

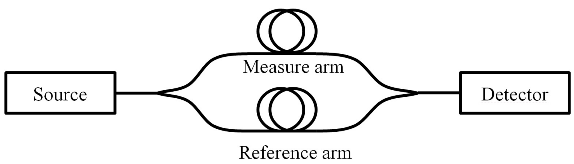

Fig. 1: Scheme of Mach-Zehnder interferometr.

In the case of Mach-Zehnder interferometer source light is split by coupler in two, representing the measuring and reference arm. Phase of the measured beam is affected by the measurand while the reference beam is experiencing a constant environment. These two beams then recombine at the second coupler and the resultant signal continues to a photodetector, which converts the optical power to electrical current. Visibility of interference depends on the relative intensity

$$I = I_0 \left[\alpha_r c_1 c_2 + \alpha_s (1 - c_1)(1 - c_2) + 2\sqrt{\alpha_r \alpha_s c_1 c_2 (1 - c_1)(1 - c_2)\, cos(\phi_r - \phi_s)} \right]. \quad (1)$$

of the measuring and reference beam, the relative state of polarization and their mutual coherence. Ideally, the relative intensity and polarization states are equal and the optical path length difference between the measured and the reference beam is much smaller than the coherence length of the light source [2].

Already published articles dealing with similar layout usable for measuring vibration, pressure, bending or temperature can be found [3], [4], [5], [6], [7], [8]. These articles are closely related to the issues addressed in this publication.

Results from previous experiments have already been published in papers [9], [10], [11], [12]. In case of [9] Mach-zehnder interferometer for movement monitoring is an early work on the configuration. Interferometric sensor based on the polarization-Maintaining Fibers discusses the use of polarization-maintaining fibers in interferometric fiber optic sensors due to increased sensitivity [10]. Fiber Bragg Grating vibration sensor with DFB laser diode uses the same measuring chain for measuring similar phenomena, but instead of interferometer bragg grating is used [11].

Unlike the above mentioned publications, this paper deals with an important aspect of practical use of optical fiber sensor namely the imposition of the interferometer arms. Therefore it is an analysis of different methods of imposing both the reference and measuring arm of the interferometer. Traditional materials used in both the construction and in everyday life were used.

2. Operating Principles

Following equations are inspired by Eric Udd and William B. Sppilman [13]. Optical phase delay of light passing through a fiber is given by:

$$\phi = n \cdot k \cdot L, \quad (2)$$

where n is the refractive index of the fiber core, k is optical wavenumber in a vacuum and $k = 2\pi/\lambda$, where λ is a light source wavelength and L is the physical length of the fiber. Also $n \cdot L$ is often referred as an optical path length.

For variations in the phase delay (2) of interferometer, we can write:

$$\frac{\mathrm{d}\phi}{\phi} = \frac{\mathrm{d}L}{L} + \frac{\mathrm{d}n}{n} + \frac{\mathrm{d}k}{k}. \quad (3)$$

With the stabilized light source k can be considered as a constant, because it depends only on the wavelength of the source. Phase change due to the measured quantities is therefore proportional to the refractive index of fiber and fiber length. Usually, changes in the pressure, temperature or magnetic field results in different contributions to dϕ via the dL and dn terms. Low–frequency processes primarily produce dL, while due changes of the coefficient of optical stress the refractive index changes.

Mach–Zehnder interferometer is compact of two couplers with coupling coefficients c_1 a c_2 and can be assumed a certain optical loss in measuring and reference arm, known as α_s and α_r. The output intensity of the interferometer can be expressed as Eq. 1, where ϕ_r is the phase shift in reference arm and ϕ_s is the phase shift in measuring arm. Definition of fringe visibility is given by standard definition which from Eq. 1 gives:

$$V = \frac{2\sqrt{\alpha_r \alpha_s c_1 c_2 (1 - c_1)(1 - c_2)}}{\alpha_r c_1 c_2 + \alpha_s (1 - c_1)(1 - c_2)}. \quad (4)$$

It should be noted that two effects have been ignored in this calculation. One is the influence of polarization. The second effect is the coherence length of the source, which should be greater than the difference in length in the arms of the interferometer ΔL. Since we have used narrowband laser diode, these effects can be considered negligible.

Provided that $\alpha = \alpha_r = \alpha_s$, so that transmission losses in both arms of the interferometer are the same. And assuming that the coupling coefficients are $c_1 = c_2 = 0,5$. Resulting fringe visibility is then, substitution into Eq. 4, $V = 1$. And intensity at the output of the interferometer can be rewritten as:

$$I = \frac{I_0 \alpha}{2} (1 + cos\Delta\phi), \quad (5)$$

where I_0 is light intensity on the input of first coupler and $\Delta\phi\,(\phi_r - \phi_s)$ is the phase difference between both arms of the interferometer. Intensity on the output of detector creates an electrical current of:

$$i = \epsilon I_0 \alpha cos(\phi_d + \phi_s sin\omega t), \quad (6)$$

where ϵ is the responsivity of the photodetector and phase difference $\Delta\phi$ may be separated into signal term of amplitude ϕ_s, frequency ω and slowly varying phase shift ϕ_d. This resultant electric signal is further processed and converted into the frequency domain, as shown in Fig. 3.

3. Experimental Setup

3.1. Introducing of the Experimental Setup

As mentioned above in case of Mach-Zehnder interferometer the light is split between two arms (Fig. 2). The light is split using the coupler which has one input and two outputs. Coupling ratio between the arms is 50 % so the light is evenly distributed to both arms. The fiber of length 210 cm is then applied to each arm. The light from the two arms are then fed into the second coupler. It is then applied to the InGaAs photodetector using the short patchcord fiber. The detector converts the optical power into an electrical current, which is further processed. As a light source DFB laser at a wavelength of 1550 nm is used. Laser diode had a stabilized operating point using the current and temperature controller. Coupled power into the fiber was in this case 1,74 mW.

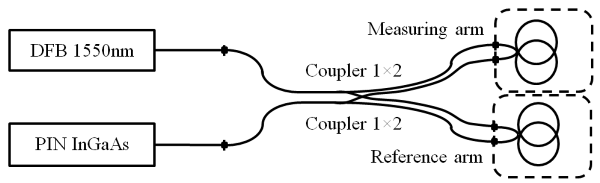

Fig. 2: Used configuration of Mach–Zehnder interferometer.

An electrical signal was fed to the LC high–pass filter with a cutoff frequency at 8 Hz via 50 Ω coaxial cable in order to suppress DC component (Fig. 3). After that was fed into a measuring card NI USB–6210 with sampling rate up to 250 kSps. The card was capturing voltage on analogue input using the application written in LabView development suite. The application also performs a discrete Fourier transform, so the voltage was transferred into the frequency domain. Hanning window function was used in our case. Peaks in calculated spectra were searched and their amplitudes written to a text file. Each measurement lasted one minute then spectrum with maximum amplitudes has been selected for further processing. The measured results were statistically processed, as will be described in the following chapter, based on ten of repeated measurements.

For excitation the rectangular signal with frequency of 160 Hz and voltage 10 V peak to peak, loudspeaker placed 1 m above fiber was used. Same signal was used for all measurement cases. Twelve different setups were measured. It was 24 measurements in total because of excitation both reference and measurement arm. Measuring and reference arms were placed on separate wooden boards. Wooden boards were placed on rubber pads to eliminate vibrations from floor.

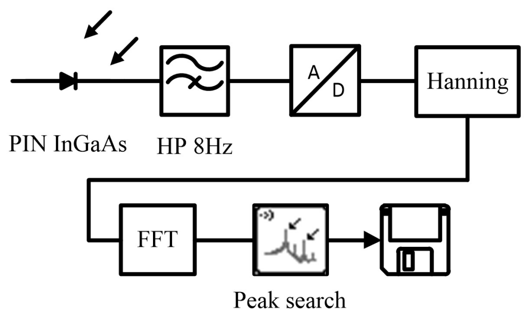

Fig. 3: Schematic diagram of electrical signal processing.

3.2. Measuring with Different Standard of Fibers and Polystyrene Boards

First two setups contained fibers of different standard in one of the interferometer arm, ITU-T G.652.D and ITU-T G.657.B, respectively. Another two measurements were with polystyrene boards. The first method was based on basic covering of the fiber with one polystyrene board, the second method was a little bit complicated, because fiber was placed between two polystyrene boards. These two boards were fixed together by double-sided adhesive tape. To achieve adequate fixation board were burdened for few minutes.

3.3. Measuring with Mounting Foam

Measuring with mounting foam was also little bit time consuming. According to the manufacturer's instructions the foam has to harden for at least 24 hours. Another obstacle was that it is very difficult or even impossible to extract fiber from fully hardened mounting foam. There were three measuring setups, which were utilizing mounting foam. First setup was foamed Tight buffered G.652.D (Fig. 4) fiber but without foamed lead fibers to the couplers. Second setup was containg the G.652.D fiber also but this time it was foamed with leads of the couplers. Finally third measuring setup was foamed Tight buffered G.657.B fiber but same as in the first case without foamed lead fibers to the couplers.

3.4. Measuring with Water and Temperature Shifts

For measuring in water was used jacketed fiber G.652.D. This arrangement was measured twice with two different temperatures of water. Firstly with warm water, temperature was from 41,8 °C at the beginning of measuring to 40,5 °C at the end of measuring. Then the measurement was repeated with cold water with

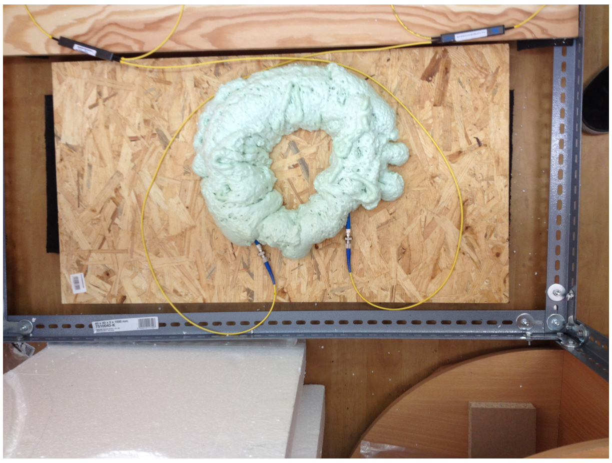

Fig. 4: Tight buffered fiber ITU-T G.652.D in mounting foam.

temperature from 24,5 °C at the beginning of measuring to 24,6 °C at the end of measuring. Total volume of water was 9 liters.

3.5. Measuring with Soil and Glue

One measuring was performed using soil. Optical cable was completely covered with two layers of soil. For completeness temperature of soil was 6,0 °C. Last measuring setup was consisted of glued jacketed fiber G.652.D glued to the wooden board by superglue.

4. Results and Discussion

For better clarity values were recalculated according to Eg. 7. Where V_1 is the voltage being measured, V_0 is a specified reference voltage for all cases and its values is 1 V, and G_{dB} is the power gain expressed in decibels:

$$G_{dB} = 20log\left(\frac{V_1}{V_0}\right). \quad (7)$$

After applying Eg. 7 there are much more convenient values in dBV as can be seen in Tab. 1. In the measurement a variety of frequencies were recorded, but as mentioned above threshold was used for distinguishing distinct frequencies and frequencies drowned in noise. Logical groups of setups were chosen, for which statistical methods described below were used. The only setup located in each group is simple placing fibers on the wooden board. From this perspective, we can say that this is a reference measurement for other imposing possibilities. Statistical methods were used for the decision about the usability of imposing in practice.

The first group is the use of traditional materials used in construction. It is the case using polystyrene boards, mounting foam and soil (Tab. 2). These setups represent a sample of possible imposing for reference arm of an interferometer. In practical terms a theoretical use of already stored fibers for interferometric measurements. Another group is the using Tight buffered fiber and bending insensitive fiber (G.657.B). Results are given in Tab. 3 and Tab. 4. Assumption of this experiments was increased sensitivity useful for special applications (single frequencies) or for general use (whole frequency band). ITU-T standard G.657.B for the possibility of a greater bending of fibers was used. This feature is particularly important in imposing of the fibers in construction and other rugged areas.

The last group is using mounting foam again for the reference branch of the interferometer. These cases are Tight buffered fiber in mounting foam, fiber in mounting foam with coupler arms (Tab. 4). The reason of this evaluation was the effect of mounting foam on a fiber. During hardening of the foam the increased pressure on the optical fiber is present. Especially Tight buffered fiber type is very sensitive to the mounting foam hardening. The suitability of the imposing of connectors and coupler arms to mounting foam were also evaluated. Table 1, Tab. 2, Tab. 3 and Tab. 4 shows the calculated medians of amplitudes in dBV for each frequency of the ten repeated measurements. For Tab. 1 and Tab. 4 statistical evaluation were performed using Kruskal–Wallis one–way analysis of variance, since there were not always fulfilled the conditions for parametric analysis of variance. Data was not distributed normally in all measurements and attempts to normalize data have failed.

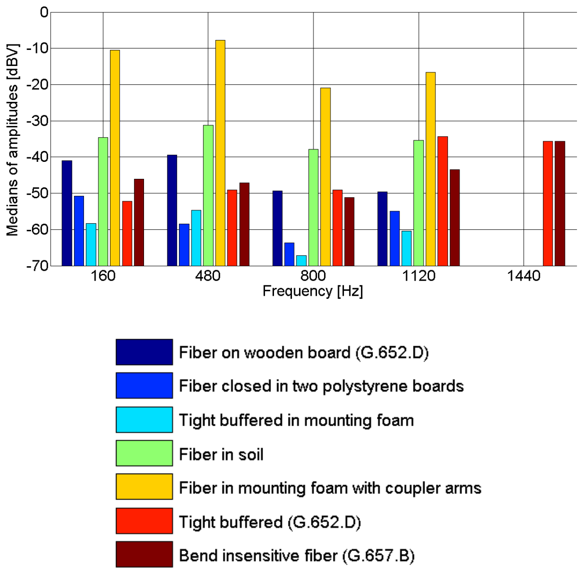

Fig. 5: Chart of statistically processed measurements.

For more clear comparison of important measured values was introduced chart of these results. Figure 5 shows a chart of calculated medians of amplitudes in dBV for significant frequencies. For Tab. 2

Tab. 1: Calculated medians of amplitudes in dBV for different setups based on ten repeated measurements (* denotes a statistically significant difference).

Frequency [Hz]	**160**	**480**	**800**	**1120**
Fiber on wooden board (G.652.D)	$-28,963$	$-30,506$	$-20,698$	$-20,394$
Fiber closed in two polystyrene boards	$-19,165$*	$-11,488$*	$-6,3615$*	$-15,089$
Tight buffered in mounting foam	$-11,714$*	$-15,33$*	$-2,8265$*	$-9,544$
Fiber in soil	$-35,444$	$-38,765$	$-32,173$	$-34,573$

Tab. 2: Calculated medians of amplitudes in dBV for different setups based on ten repeated measurements (* denotes a statistically significant difference).

Frequency [Hz]	**160**	**480**	**800**	**1120**	**1440**
Fiber on wooden board (G.652.D)	$-21,401$	$-20,952$	$-27,619$	$-25,783$*	$-29,275$*
Tight buffered (G.652.D)	$-17,776$*	$-20,864$	$-20,959$*	$-35,663$	$-34,298$

Tab. 3: Calculated medians of amplitudes in dBV for different setups based on ten repeated measurements (* denotes a statistically significant difference).

Frequency [Hz]	**160**	**480**	**800**	**1120**	**1440**
Bending insensitive fiber (G.657.B)	$-23,895$	$-22,847$	$-18,774$*	$-26,501$*	$-34,298$
Tight buffered (G.652.D)	$-17,776$*	$-20,864$*	$-20,959$	$-35,663$	$-34,298$

Tab. 4: Calculated medians of amplitudes in dBV for different setups based on ten repeated measurements (* denotes a statistically significant difference).

Frequency [Hz]	**160**	**480**	**800**	**1120**
Fiber on wooden board (G.652.D)	$-28,963$	$-30,506$	$-20,698$	$-20,394$
Tight buffered in mounting foam	$-11,714$*	$-15,33$	$-2,827$*	$-9,5435$*
Fiber in mounting foam with coupler arms	$-59,447$	$-62,264$	$-49,095$	$-53,422$

Tab. 5: Calculated arithmetic mean of amplitudes in dBV for different setups based on ten repeated measurements.

Frequency [Hz]		**160**	**320**	**480**	**800**	**1120**	**1440**	**1760**	**2080**
Fiber on wooden board (G.652.D)	Meas. [dBV]	$-22,116$	-	$-21,251$	$-27,869$	$-26,018$	$-29,477$	-	-
	Ref. [dBV]	$-29,592$	-	$-30,221$	$-21,109$	$-20,777$	-	-	-
Bending insensitive fiber (G.657.B)	Meas. [dBV]	$-23,808$	-	$-23,125$	$-18,583$	$-26,311$	$-26,311$	-	$-31,448$
	Ref. [dBV]	-17.201	$-16,238$	-	$-22,431$	$-23,735$	-	-	-
Fiber covered with polystyrene board	Meas. [dBV]	$-30,250$	-	$-27,460$	$-21,645$	$-23,442$	-	-	-
	Ref. [dBV]	$-21,011$	$-31,210$	$-30,140$	$-19,792$	$-22,618$	-	-	-
Fiber closed in two polystyrene boards	Meas. [dBV]	$-13,096$	-	$-8,078$	$-8,078$	$-6,994$	$-14,504$	$-13,670$	-
	Ref. [dBV]	$-18,514$	-	$-11,530$	$-6,399$	$-16,695$	$-12,181$	-	$-11,707$
Tight buffered (G.652.D)	Meas. [dBV]	$-18,576$	-	$-21,078$	$-21,244$	$-36,374$	$-34,308$	-	-
	Ref. [dBV]	$-15,662$	-	-	-	-	-	-	-
Tight buffered in mounting foam	Meas. [dBV]	$-13,462$	-	$-13,194$	$-5,082$	$-16,538$	-	$-17,506$	-
	Ref. [dBV]	$-11,787$	-	$-15,264$	$-2,984$	$-9,680$	-	-	-
Fiber in mounting foam with coup. arm.	Meas. [dBV]	$-13,462$	-	$-13,194$	$-5,082$	$-16,538$	-	$-17,506$	-
	Ref. [dBV]	$-11,787$	-	$-15,264$	$-2,984$	$-9,680$	-	-	-
Insensitive fiber in mounting foam	Meas. [dBV]	$-72,571$	-	$-75,452$	$-73,416$	$-75,940$	$-74,135$	-	$-79,461$
	Ref. [dBV]	$-65,880$	-	-	$-68,940$	$-66,728$	$-68,046$	$-77,176$	$-76,978$
Fiber in warm water	Meas. [dBV]	$-31,524$	-	-	$-24,867$	$-26,770$	$-32,594$	-	-
	Ref. [dBV]	-	-	-	$-11,706$	-	-	-	-
Fiber in cold water	Meas. [dBV]	-	-	$-29,801$	$-18,182$	$-29,597$	-	-	-
	Ref. [dBV]	$-27,964$	-	$-32,635$	$-22,175$	-	$-24,567$	$-35,083$	-
Fiber in soil	Meas. [dBV]	$-27,964$	-	$-32,635$	$-22,175$	-	$-24,567$	$-35,083$	-
	Ref. [dBV]	$-34,079$	-	$-38,511$	$-32,178$	$-34,666$	$-28,057$	$-36,430$	-
Fiber glued to wooden board	Meas. [dBV]	-	-	$-56,591$	$-62,059$	-	-	-	-
	Ref. [dBV]	-	-	$-54,998$	$-53,841$	$-62,108$	$-63,479$	-	-

and Tab. 3 statistical evaluation ware performed using Mann–Whitney–Wilcoxon non–parametric significance tests since there were not always fulfilled the conditions for parametric tests.

5. Conclusion

Measured results showed that the different installation of the reference and measuring arm of the interferometer gives the effect of changing the sensitivity of the measured. We were able to increase the sensitivity of interferometric sensor by installation of optical fibers to traditional materials used in construction. Polystyrene panel has proved the best results due to the easy handling and low cost. In the case of attempts to achieve the best sensitivity by modifying the configuration of the reference arm we would choose the installation with mounting foam. In contrast coupler arms and connectors installed in mounting foam proved wrong. This phenomenon was caused by hardening of the foam. For the measurements at lower frequencies is the absence of the jacket advantageous, but for higher frequencies it is advisable to have the measuring arm fully protected by the jacket. In practice the tight buffered fiber is not suitable for installation. Jacketed fibers are used for their solid and elasticity. These experiences exclude Tight buffered fibers in practical use.

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