3x3 coupler Mach-Zehnder interferometric strainmeter

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This work is aimed at developing a new type of tools for seismic-deformation monitoring of large-scale man-made objects (buildings and structures) to solve the problems of forecasting and preventing emergency situations during the operation of these objects. Monitoring systems based on the proposed strainmeters can be used, for example, to monitor the state of rock masses in mines. Today, seismoacoustic receivers are used to monitor such objects. The inclusion of deformation monitoring tools in such systems will significantly improve the accuracy of forecasting emergency situations at the controlled object. At present, long-base strainmeters with a base length of 20 to 100 meters are widely represented by stationary laser interferometers. There are also strainmeters with a small base (on the order of several centimeters) based on fiber-optic Bragg gratings. At the same time, the most popular rapidly deployable strainmeters with a base length of 1 to 10 m are practically absent, and currently used string mine strainmeters do not meet modern requirements for monitoring systems.

3X3 COUPLER MACH-ZEHNDER INTERFEROMETRIC STRAINMETER WITH PASSIVE PHASE DEMODULATION

To register seismic vibrations by the strainmeter, a scheme of a fiber-optic Mach-Zehnder interferometer with a 3x3 coupler was used [1]. The advantages of this circuit are compactness, immunity to electromagnetic interference, high sensitivity and a large dynamic range of the received signal.

The interferometric strainmeter is based on Mach-Zehnder interferometer (Fig.1), which consists of fiber-optic light guides of the reference arm (4), the sensing arm (3) with an input Y-splitter (2) and a 3x3 coupler (5) at output. Multi-turn optical-mechanical converter (MOC) is used as a sensitive element of the strainmeter [2]. MOC is integrated into the measuring arm of the Mach-Zehnder interferometer. The optical elements, multiturn optical converter, laser source and electronics are installed in metal casing (Fig.2). The data obtained from the strainmeter were processed using the algorithm described in [3].

MATHEMATICAL MODEL OF THE STRAINMETER AND THEORETICAL SENSITIVITY

Let us consider the stationary physical model of the strainmeter, which can be described as connection of an elastic cable (the spring with stiffness k_w, length l_w and an multiturn fiber coil, in which the role of the second spring is played by N sections of the light guide with a length l_m. (Fig. 3).

If you increase the distance between point 2 and 1, the springs lengthen by:

$$\Delta L = \Delta l_w + \Delta l_m \tag{1}$$

In this case, the increase in the tension force F_t caused by the elongation compensates for the increase in the tension force of the sections of the fiber F_m, because $F_t = F_m$. Hence, we obtain the formula from the tension forces of individual fibers

$$F_t = F_m = 2NF_f\,, \tag{2}$$

where F_f is the tension force of one section of the fiber, N is the number of turns of the fiber in the multiturn optical converter. Provided that the elongation of the fibers is not higher than 1%, Hooke's law is fulfilled and it becomes possible to rewrite expression (2) in the form

$$k_w \Delta l_w = 2Nk_f \Delta l_f\,, \tag{3}$$

where k_w is the coefficient of elasticity of the wire, k_f is the coefficient of elasticity of one section of the fiber.

From (1) it follows that, $\Delta l_w = \Delta L - \Delta l_m$, hence

$$\Delta l_m = \frac{\Delta L}{2N\frac{k_f}{k_w}+1} \tag{4}$$

Then the total lengthening of the fiber of the measuring arm of the interferometer

$$\Delta l_f = 2N\Delta l_m = \frac{2N\Delta L}{2N\frac{k_f}{k_w}+1} = \frac{\Delta L}{\frac{k_f}{k_w}+\frac{1}{2N}} \tag{5}$$

This equation shows interferometer sensing arm elongation ($\Delta l_f)$ dependence as a function of total strainmeter length increase (ΔL), stiffness of elastic wire (k_w), and a mechanical characteristic of MOC (stiffness coefficient of optical fiber strand (k_f) and their total count in the coil N)

It can be seen from (5) that with an increase in the coefficient of elasticity of the wire (k_w) and with an increase in the number of turns in the MOC, the amount of fiber elongation, and hence the sensitivity of the strainmeter, will increase.

If the length of the MOC is increased by Δl_m, the phase difference increase can be described as:

$$\Delta\phi = 2\pi\frac{n}{\lambda}\Delta l_f = 2\pi\frac{n}{\lambda}\cdot 2N\Delta l_m = 4\pi N\frac{n}{\lambda}\cdot\Delta L \tag{6}$$

We can substitude (5) to (6) to get a phase difference for a strainmeter with a elastic wire:

$$\Delta\varphi = 2\pi\frac{n}{\lambda}\Delta l_f = 2\pi\frac{n}{\lambda}\frac{\Delta L}{\frac{k_f}{k_T}+\frac{1}{2N}} \tag{7}$$

From (7) a theoretical strainmeter sensitivity can be derived:

$$\frac{\Delta\varphi}{\Delta L} = 2\pi\frac{n}{\lambda}\frac{1}{\frac{k_f}{k_w}+\frac{1}{2N}} \tag{8}$$

EXPERIMENT DESCRIPTION

The multiturn optical converter of fiber-optic strainmeter (1) is pulled by motorized optical translator (3,4) via tested elastic wire (2). The optical translator movement is controlled by laser triangulation sensor (5). All equipment is installed on optical table (6). The triangulation sensor data and raw data from three-channel Mach-Zehnder interferometer is digitized by ADC for further processing in Matlab software on PC (Fig.4).

Main hardware characteristics:
Fiber interferometer laser source: Nolatech DFB-1550 -8DL laser diode (λ=1550 nm)
Fiber interferometer detectors: 3x Nolatech FDM-14-2K InGaAs PIN photodiodes
Laser triangulation sensor: Riftec RF603-15/5, maximum measurable distance 5 mm, 0.5 um resolution
ADC: Zetlab Zet230, 22 effective bits and 25 kHz discretization per channel

RESULTS

To avoid test stand damage, optical translator movement was reduced for steel and kevlar wires.
Fig.5 shows sensitivity increases to theoretical constant value as test wire tension growth with corresponding increase of total length ΔL. The strainmeter sensitivity (${}^{\Delta\varphi}/_{\Delta L}$) was found by division of phase difference output of strainmeter ($\Delta\varphi$) by recorded elogation length (ΔL). Due to different initial tension and inequality of wire connection two different experiments for each wire was conducted. Color curves shows two experimental results for corresponding material (yellow and red for kevlar, blue and dark blue for steel, green and purple for polyamide). Irregularities of sensitivity of steel wire can be explained as a lack of uniformity of wire different strand tension. As opposed to several strands of steel wire, there were used single strand of polyamide and a multiple thin strands of kevlar. Theoretical sensitivity (dashed lines) was calculated by (8), the values of $\lambda = 1550$ nm, $n = 1{,}46, k_f = 5720\frac{N}{m}, N = 20$ were used.

CONCLUSIONS

The mathematical model of fiber-optic Mach-Zehnder strainmeter was developed, and the equation of theoretical sensitivity was derived. The results shows a good match between theoretical and experimental data. Based on the results obtained in this work, another strainmeter prototype was created, which was tested in the conditions of the underground mine. Corresponding results will be described in subsequent publications.

REFERENCES

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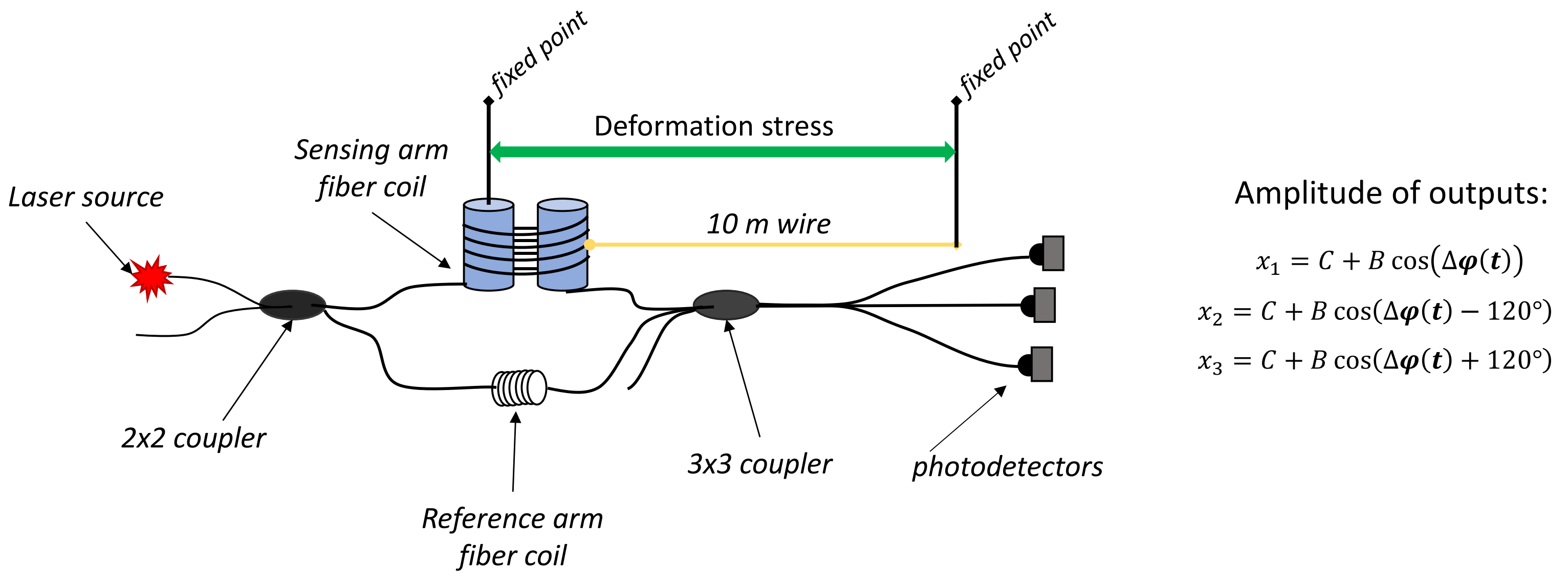

Amplitude of outputs:

$$x_1 = C + B\cos\big(\Delta\boldsymbol{\varphi}(\boldsymbol{t})\big)$$
$$x_2 = C + B\cos(\Delta\boldsymbol{\varphi}(\boldsymbol{t}) - 120°)$$
$$x_3 = C + B\cos(\Delta\boldsymbol{\varphi}(\boldsymbol{t}) + 120°)$$

Fig.1 Optical design of fiber-optic Mach-Zehnder strainmeter.

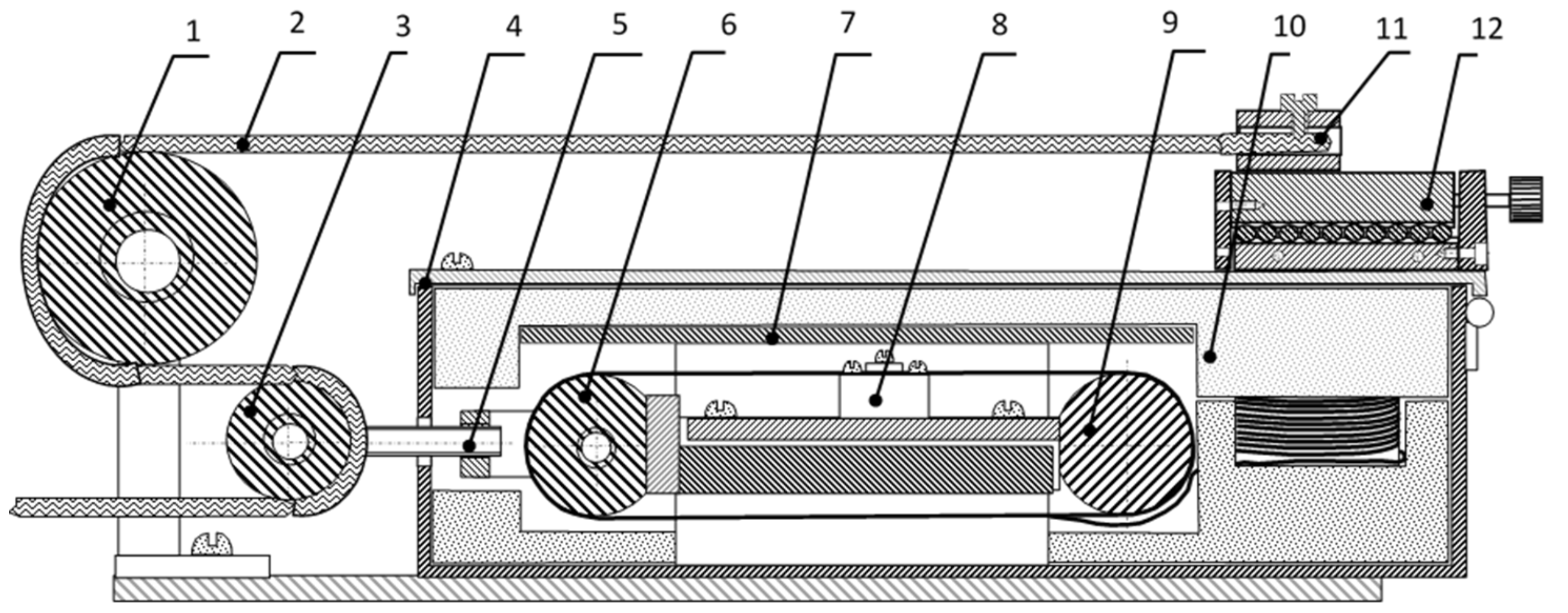

Fig.2 Mechanical design of fiber-optic Mach-Zehnder strainmeter.
1 - pulley 1; 2 - cable; 3 - pulley 2; 4 - casing; 5 - p-shaped bracket and rod; 6 - movable cylinder of the fiber optic coil; 7 - protective plate; 8 - fiber clamp; 9 - cylinder connected to the body; 10 - foam filling; 11 - cable fastening; 12 – optical translator.

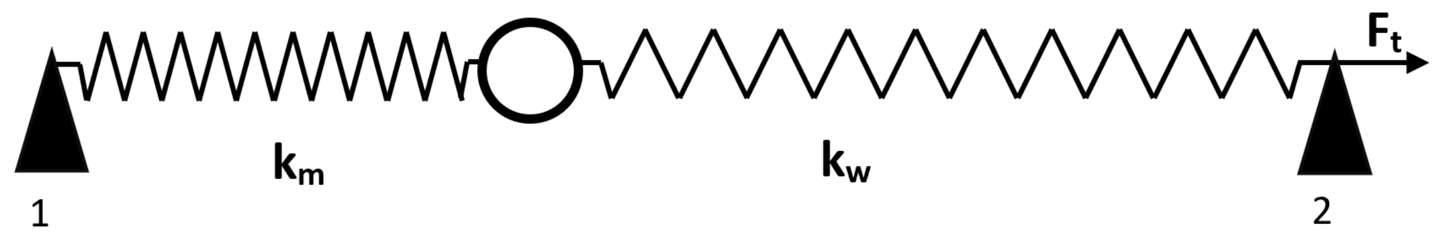

Fig.3 Physical model of strainmeter

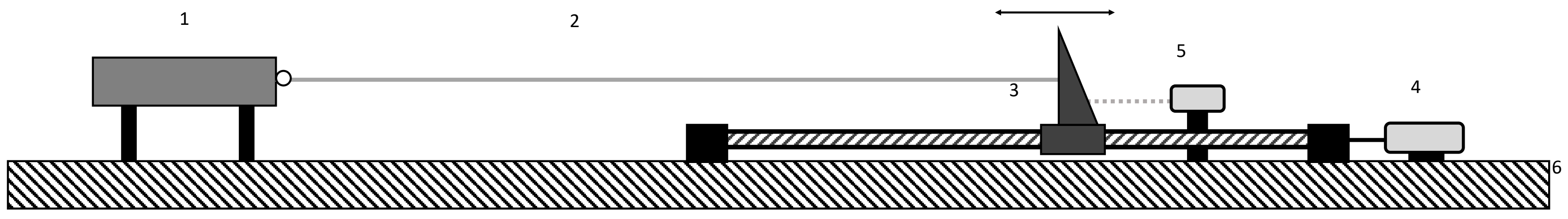

Fig.4 Test stand design. 1. Fiber-optic strainmeter, 2. elastic wire, 3. optical translator, 4. servo motor, 5. laser triangulation sensor, 6. optical table. The arrow shows optical translator movement direction.

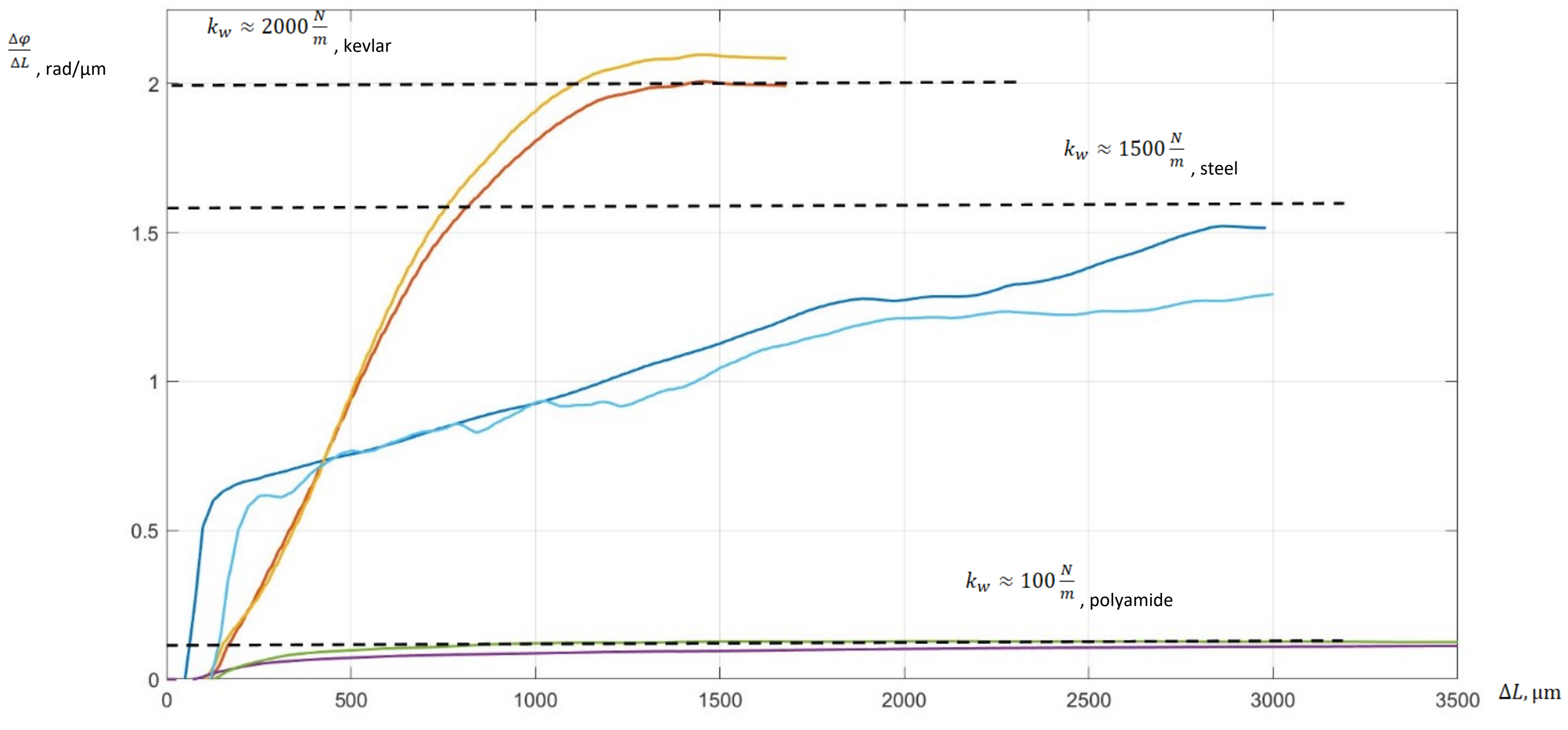

Fig.5 Sensitivity (${}^{\Delta\varphi}/_{\Delta L}$) in rad/ µm for elastic cable from 3 different materials: kevlar (red/yellow curve), steel (blue/dark blue curve) and polyamide (green/purple curve) with different k_w. Dashed lines indicate theoretical sensitivity for three materials.