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WIDE-BAND OPTICAL FIBRE SYSTEM FOR INVESTIGATION OF MEMS AND NEMS DEFLECTION

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Abstract

In this work the construction of experimental setup for MEMS/NEMS deflection measurements is presented. The system is based on intensity fibre optic detector for linear displacement sensing. Furthermore the electronic devices: current source for driving the light source and photodetector with wide-band preamplifier are presented.

Keywords: fibre optic sensors, amplitude detection, intensity detection, MEMS/NEMS deflection measurement.

1. Introduction

The micro- and nano-electro-mechanical systems (MEMS and NEMS) with micro and nanomechanical resonators form a group of extremely sensitive devices [1], capable of measuring mass differences on the order of femtograms, and force differences on the order of piconewtons. The sensitivity and detection resolution increase when the device dimensions are scaled down. This entails however that the operating frequencies reach the MHz range and application of elaborated measuring equipment is needed [2]. In order to detect the parameters of interest, the microstructure measuring equipment has to be able to work with very small distances at high frequencies. In the course of our experiments, the optical-fibre based detector had been deemed as a reasonable tool for such high frequency measurements of mechanical displacements [3]. The constraints put on such a system include a cut-off frequency in the MHz range and nanometer range resolution [4]. By application of low-noise current sources for biasing of light sources, low noise and wideband preamplifier electronics and through the design of a fibre optic setup we fabricated a system with 2 MHz cut-off frequency and 15 nm resolution (with an estimated displacement sensitivity of 10.6 pm/Hz^{-2}). A calibration method, involving the use of an auxiliary piezoelectric transducer, is also presented.

2. Intensity sensor system

Intensity sensors are a class of fibre devices sensitive to wave amplitude modulation. The primarily considered problems when constructing such devices are reflection [5], and optical power losses on microbendings within the fibre [6]. Intensity reflective sensors with their legible construction maintain a precise conversion rate and transducing characteristic [7].

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A schematic of the system used is shown in Fig. 1. The central element of the setup is a -3 dB signal coupler. The first fibre-arm inputs a signal from the light source to the coupler. The second arm is the fibre transceiver that directs the light onto the structure. After reflection from the measured object, the fibre arm couples the beam back to the fibre system [8]. The third arm transmits the light back to the detector.

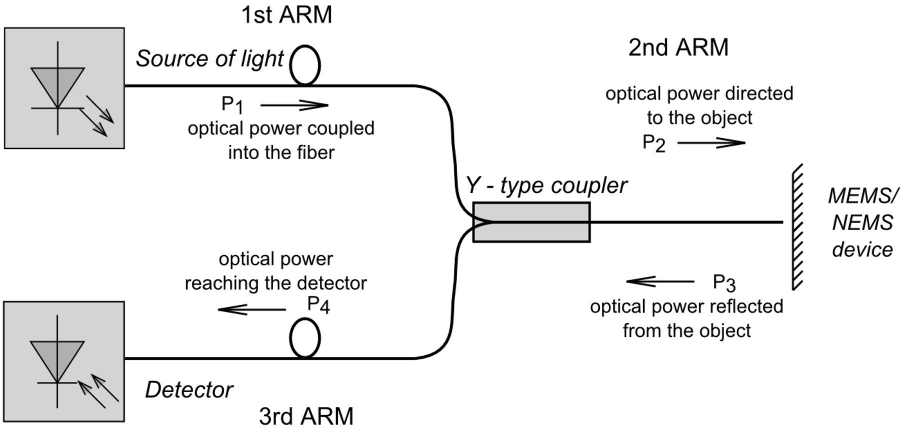

Fig. 1. Intensity sensor scheme.

Analysis of the structure's deflection and thereby detecting changes in its distance from the fibre end is achieved by detecting changes in the received optical signal at the detector. The processing characteristic of the system is monotonic and the sensitivity depends on the absolute distance between the fibre end and the structure surface.

3. Geometrical optics analysis of optical power losses

The analysis of losses was based using geometrical optics. An in-depth look at what happens when the measuring signal is reflected and re-coupled to the fibre system was performed. The changes of the optical power surface density were measured in the following setup (Fig. 2).

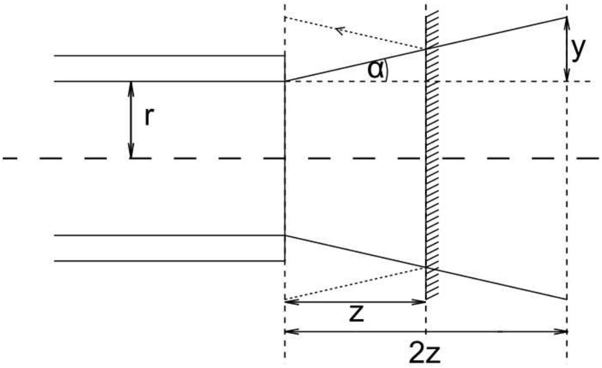

Fig. 2. Intensity sensor – light reflection from the measured object.

We assumed that the beam of radiation going out of the fibre is forming a cone of light with an angle dependent on the numerical aperture of the fibre used. In addition, a homogeneous distribution of optical power density in any plane parallel to the fibre end was assumed. Then the surface density of optical power at the output of the fibre is

$$\rho_1 = \frac{P_2}{\pi r^2}, \tag{1}$$

where P_2 is the value of the outgoing optical power incident on the structure, and r is the fibre radius. Assuming a reflectance coefficient value equal to 100%, the density of the optical power of the image of the receiving arm is estimated as shown in Fig. 2. Skipping the losses associated with reflections from the rear end glass-air interface, the fibre bundled an optical power density of radiation at the end of the fibre, which, after reflection, was calculated to be:

$$\rho_2 = \frac{P_2}{\pi\left\{r + 2z \cdot \tan\left[\arcsin\left(NA\right)\right]\ \right\}^2}, \tag{2}$$

where z - the distance between the reflecting surface and the fibre, NA – numerical aperture. P_3, the value of the optical power coupled back into the system, is then equal to:

$$\rho_2 = \frac{r^2}{\pi\left\{r + 2z \cdot \tan\left[\arcsin\left(NA\right)\right]\ \right\}^2}\mathrm{P}_2, \tag{3}$$

4. Construction of an optical measuring system

A Y-type coupler made of multimode fibres 62.5/125 microns was applied, with about -3.2 dB loss. The numerical aperture of the bundles was 0.242. The light source was a light-emitting diode HFBR1414 TZ with a wavelength of 850 nm. The diode was used with an ST adapter, allowing direct connection with the optical fibre system. As a detector, a silicon photodiode (FDS02 Thorlabs) with an FC/PC connector was used [9]. The sensitivity of the range used (for a wavelength equal to 850 nm) is 0.4 A/W.

The intensity sensor measuring head was placed on a movable stage with a micrometer resolution screw with 1 micron resolution (Fig. 3). The reflecting surface acting as a measuring surface of the investigated structure was mounted on the piezostack with known characteristics of deflection, in order to determine the sensitivity and resolution of the constructed sensor system.

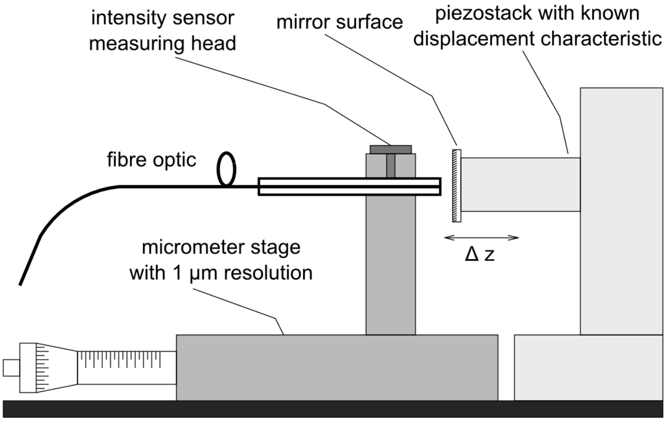

Fig. 3. Setup for calibration of sensitivity and resolution of the intensity sensor.

5. Determination of sensitivity and resolution of intensity sensor

A voltage-current converter was used as the light emitting diode controller. This system provides high-stability current up to 100 mA. A transistor switch, a mechanical latch and a metal-semiconductor junction are used to protect the LED against reverse polarization. Elements with low temperature coefficients of current and voltage are used in this construction, ensuring stability of current below 0.5 μA/K.

We designed and fabricated a wideband and low noise transimpedance amplifier, integrated with an electronic preamplifier for conversion of the optical signal from the photodetector. The block diagram is shown in Fig. 4. The circuit allows reverse biasing of the photodetector with a voltage of 10 V which reduces the detector response time.

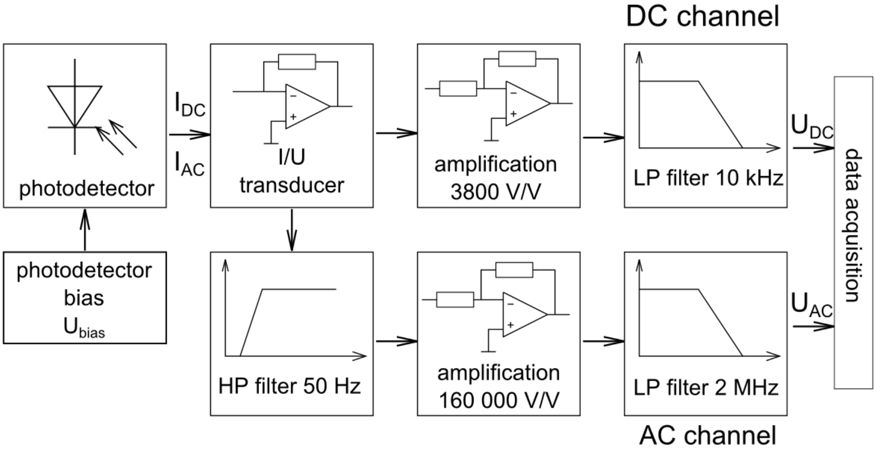

Fig. 4. Block diagram of the electronic preamplifier circuit.

The transimpedance amplifier was implemented with an operational amplifier AD712 (with bias current I_{bias} = 75 pA). A transimpedance value of R_f = 47 kΩ is used. The voltage signal is then split into two channels: DC and AC coupled. Gain and bandwidth for each channel can be adjusted independently. For DC and AC channel gain was set to 3800 V/V with 10 kHz bandwidth and 160000 V/V with bandwidth 2 MHz, respectively. These values correspond to sensivities of optical power conversion: DC – 0.71 V/nW and AC – 3 V/nW. In the designed circuit, the photodiode's dark current with 10V reverse bias has value of I_{dark} = 18.4 pA.

6. Determination of sensitivity and resolution of intensity sensor

In the measurements of the static transduction characteristics of the constructed intensity reflective fibre optic sensor, optical power P_1 equal to 60,26 µW was coupled into the first arm. (for LED current I_{HFBR} = 60 mA). The measured optical power values P_4, recorded at the photodetector and the calculated values resulting from geometrical optics assumption $P_{4\ calc}$ (P_3 values form Eq. 3 with coupler loss taken into account) are shown in Fig 5.

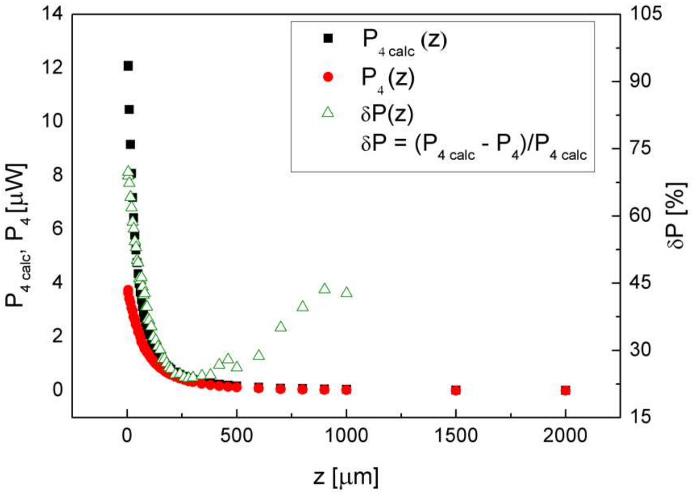

Fig. 5. Detected optical power vs. mirror-fibre distance – comparison with calculated values.

Taking losses at the coupler into account, and estimating the distance between the end of the fibre and the mirror equal to 10 microns, optical power $P_{3\ calc}$ is 20.38 µW, while $P_{4\ calc}$ is 10.21 µW. In the experiment, recorded power was equal to 3.42 µW.

In order to determine the resolution of the manufactured system, an auxilliary piezoelectric PI reference stack has been used as a reference for displacement (5mm × 5mm × 2mm in dimensions) [10]. The piezostack's deformation had been previously measured on a microstructure characterizer system. In this way the frequency spectrum of piezostack deflection was determined in a bandwidth of up to 20 kHz. The microstructure characterizer system used a SIOS SP120S vibrometer [11] as the deflection sensor. The maximum hardware resolution of the vibrometer is 0.02 nm in the range 0 – 500 kHz. Fig. 6 presents the electromechanical spectrum of the reference piezostack used for the system calibration.

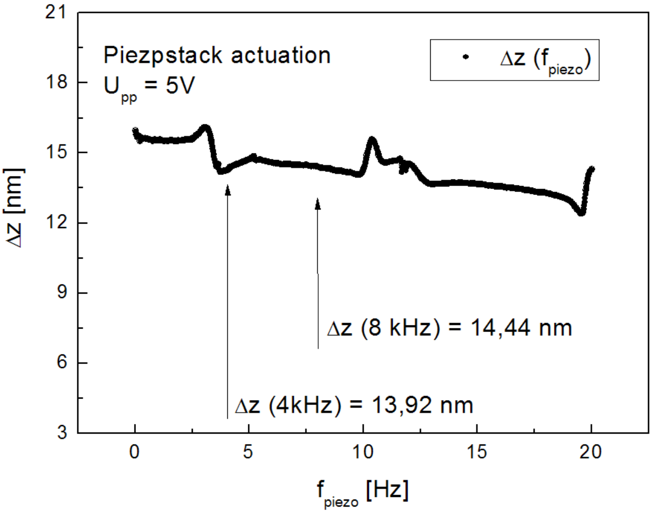

Fig. 6. Expansion of the reference piezostack.

The sensitivity measurement of the system was performed by changing the distance between the optical fibre and the mirror from 0 to 300 microns. The piezostack was stimulated with a sinusoidal signal with a frequency f_{piezo} = 4 kHz and amplitude U_{pp} = 5 V. Similar to the static measurement, the LED source of light was supplied with a current intensity I_{HFBR} = 60 mA, allowing to couple an optical power P_1 = 60.26 μW into the fibre optical system. The resulting dynamic characteristics is shown in Fig. 7.

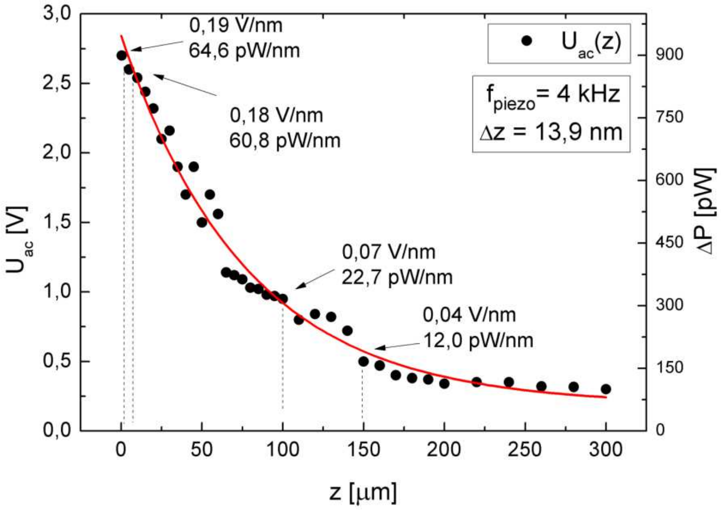

Fig. 7. Voltage amplitude (displacement amplitude registered through the detecting device) as a function of the sample-probe distance.

In every measured point of the intensity sensor's static processing characteristics, the response of piezostack vibrations in the AC channel (Fig. 4) has been measured. The resulting signal was recorded using an oscilloscope with 16-fold averaging (Fig. 8).

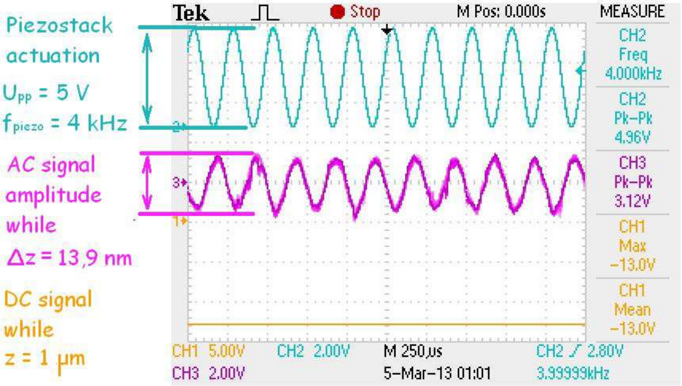

Fig. 8. System resolution measurement for given distance z and displacement Δz.

Based on the measured dynamic characteristics of the system, a sensitivity from S = 0.94 V/nm (64.6 pW/nm) at a distance of the mirror z = 0 microns to S = 0.4 V/nm (12.0 pW/nm) for z = 150 microns was calculated. For an object vibrating with an amplitude of several nanometers, investigations at distances of about 150 microns from the end of the fibre require an increase in the signal-to-noise ratio by improving the selectivity of the processing path.

6. Summary

Using the manufactured intensity sensor based system, investigation of MEMS and NEMS devices will be possible, with several nanometers of deflection amplitude in the frequency range up to 2 MHz. The bandwidth may be tuned in the range up to 2 MHz, and the system can be extended by additional amplifying stages. Such an approach allows us to finely tune the system in order to obtain a maximal resolution per structure. Adding to that a small diameter of the optical fiber, the proposed system is to be integrated easily with NEMS and MEMS devices.

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