Optical Structure with PDMS Microfibre for Displacement Measurement

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Abstract: We proposed, prepared and demonstrated an optical structure consists of conventional single-mode optical fibres and a bend PDMS microfiber. The structure forms Mach-Zehnder interferometer with variable length of an air arm. The structure can be used for sensing of various physical quantities as temperature, humidity, volatile organic compounds, etc. We demonstrated its usage by displacement measurement. For determination of a displacement we used a change of interference pattern period. The sensitivity of proposed structure is 0.027 nm/μm.

1 INTRODUCTION

Optical fibre interferometers are due to their very high sensitivities and compactness often used for the measurement of various physical quantities as the temperature (Li, 2012), (Luo, 2015), the refractive index (Tian, 2008), the pressure (Xu, 2012), etc.

For purpose of miniaturisation of optical fibre interferometers it is possible to use a microfibre or a nanofibre. An advantage of use such fibres is bend non-sensitivity and a low bending loss due to their large refractive indices contrast (Chen, 2013).

In recent years a several formation of interferometers with microfibres have been published. For example, Mach-Zehnder interferometer (MZI) structure assembled from silica and tellurite glass microfibre (Li, 2008) and MZI structure made of the polymethylmethacrylate (Li, 2014).

Displacement fibre sensors can be performed in different ways. It is often used sensors based on fibre Bragg grating. A sensitivity of such sensor proposed in (Shen, 2011) is 0.058 nm/mm in displacement range of 0 - 20 mm. Another possibility is the interferometric technique. In (Chen, 2013) a sensitivity of proposed the bent fibre Mach-Zehnder interferometer structure is 0.835 nm/μm in range of 350 μm.

In this manuscript we report a preparation of polydimethylsiloxane (PDMS) microfiber which forms one arm of Mach-Zehnder interferometer. PDMS possess properties such a hydrophobility, hydrolytic stability non-flammable, high chemical stability, optically clear and its refractive index is close to that of glass (Kacik, 2016).

Such optical structure we used for a displacement determination. When a length of air arm is changed, the period of interference pattern will change. So we determine the structure response on the displacement. The main advantage of such structure is that consists adjustable air optical line in one arm and microfibre in second. Such interferometer could be used in applications where the measurands will only affect the properties of microfibre (for example for sensing of volatile organic compounds). A disadvantage is its sensitivity to many various physical quantities and the need to differentiate between them.

2 OPTICAL MICROFIBER MZI FABRICATION

For preparation of optical microfibre integrated between two conventional single-mode optical fibres (SMFs) we used liquid silicone Sylgard 184 (Dow Corning) supplied as two-part liquid component kits. After mixing the pre-polymer and curing agent at ratio of 10:1, the prepared elastomer was applied on the cleaved ends of conventional optical fibres (Figure 1.a). Thereafter, we connected optical fibre ends covered by PDMS (Figure 1.b). Then PDMS

Kacik D. and Martincek I.
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was cured at room temperature for about 10 hours. After that time the PDMS elastomer achieved suitable consistency for microfibre drawing. Axial alignment of SMFs with PDMS joint was mechanically adjusted by 3D microstages to obtain maximal transmitted signal through the PDMS join at wavelength 1550 nm. PDMS microfibre was created by gradual distancing of single-mode fibres ends (Figure 1.c) together with in-situ controlling the axial position by signal level. When the length and the diameter of microfibre was sufficient the PDMS microfibre was cured at the room temperature for another 40 hours. The prepared optical microfiber had a diameter of 7 micrometres and 270 micrometres in length. Then we decreased the distance between SMFs ends what caused the bend of microfiber (Figure 1.d).

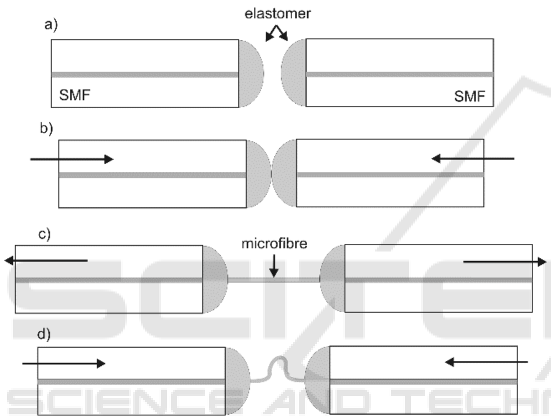

Figure 1: Illustration of optical microfiber MZI fabrication. a) PDMS deposition on SMFs ends. b) connection of fibre ends. c) coaxial drawing. d) MZI formation.

3 MACH-ZEHNDER INTERFEROMETER

The light transmitted through the input fibre is coupled to the optical microfibre and then recoupled to the output fibre of the prepared structure. But for suitable bend of microfibre it is possible to obtain the state when the light transmitted through the SMF is split at the end of input SMF covered by PDMS: the part of light is still transmitted through the microfibre and another part is propagated in coaxial direction to core of input fibre (so the light propagates in the air). By proper adjusting of output fibre position it is possible to recoupled the light transmitted through the air to the output fibre (Figure 2).

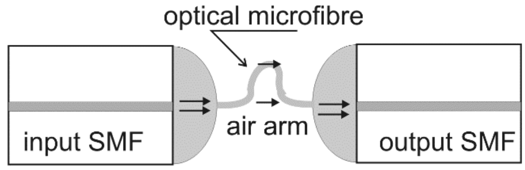

Figure 2: Schematic of Mach-Zehnder interferometer consists of air arm and optical microfiber in other arm.

If the optical path difference (between light transmitted through the microfibre and air) is smaller than coherence length of an optical source one can observe the interference of light. Example of the spectral dependence of the interference pattern is shown in Figure 3.

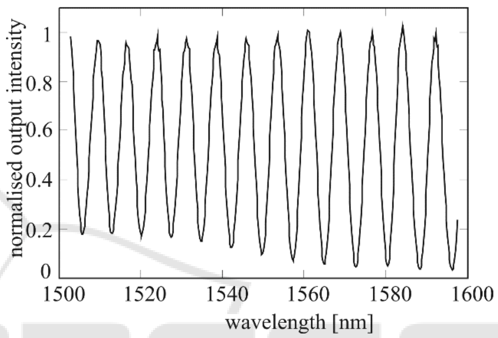

Figure 3: Example of spectral dependence of interference pattern of prepared microfibre MZI.

According to Figure 3 we assume that the interference pattern is formed by two beams, one guided through the microfibre and second one through the air. For this case the output intensity can be expressed as

$$I(\lambda) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\beta(\lambda)z_1 - \frac{2\pi n}{\lambda}z_2\right) \quad (1)$$

where I_1 and I_2 are intensity of light that coupled to the core of the output SMF from the microfibre and from air arm, respectively, β is phase constant of the beam (mode) guided through the microfibre, z_1 is the length of the microfibre, z_2 is length of air arm, n is refractive index of air and λ is the wavelength of the propagating light in vacuum.

4 DISPLACEMENT MEASUREMENT

Similarly, as it was mentioned before, the prepared structure is sensitive to various physical quantities.

So, for the measurement of the displacement the temperature, the pressure and the humidity in the room were monitored and keep constant. For the spectral dependence measurement of the interference pattern of the prepared microfiber MZI the broadband light source coupled to the fibre (SLED Safibra OFLS-6) with central wavelength at 1500 nm and 100 nm spectral range was used. The output SMF was connected to and the spectrum recorded by an optical spectrum analyser (Anritsu MS9710B), with a resolution of 0.07 nm. The structure consisting from SMFs ends covered by PDMS and optical microfibre was placed on differential micrometre stages in order to adjust the relative positions of SMFs and increasing the length of air arm. The change of the length of air arm was detected by inductance probe, which allow one to distinguish variations of the length with resolution of hundredth of a micrometre.

At first, the reproducibility was investigated. We set the length of air arm to value 80 micrometres and measured 10 times spectral dependences with time difference about 5 minutes between each measurement. The spectral shift of interference pattern was observed. It could be caused by very slightly change in temperature. But we were interested if it also occurs the change in interference pattern period. The determination of interference pattern period was done for two neighbouring maxims at (close to) wavelength 1550 nm. The average value of period was 7.491 nm and its root mean square was determined to 0.005 nm.

The structure is characterised by possibility to change the length of air arm while the length of the second arm is constant. For this reason the prepared structure can be used for displacement measurement. We were measured spectral dependencies of interference pattern for lengths of the air arm from 45 µm to 130 µm. Example of spectral dependencies (for the lengths of air arm 45 µm, 60 µm and 70 µm) in the investigated wavelength range from 1500 nm to 1600 nm are shown in Figure 4.

As it can be seen from dependencies shown in Figure 4 for particular length of air arm the power level is changed. We assume that the intensity of light propagated through the microfibre was the same (for small change of length of air arm) but what change was the intensity of light recoupled to the output fibre due to change of the microfibre bend. It means that there was a change in emission/excitation of conditions. In addition, there is also a change in period of interference pattern.

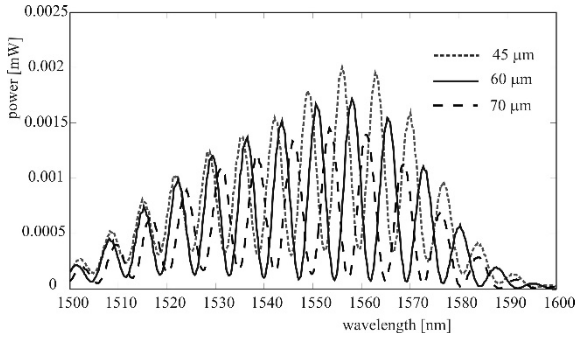

Figure 4: Spectral dependencies of interference pattern for lengths of air arm 45 µm, 60 µm and 70 µm. The spectral dependencies are not corrected to spectral characteristic of light source.

In Figure 5 there is shown the values of period of interference pattern for particular length of air arm. Determined values of period of interference pattern obtained from measured spectral dependencies of interference pattern can be fitted by linear function. The function is also shown in Figure 5. There is good correlation between determined values of interference period and linear function. The discrepancy could be caused by inaccurate determination of maxims wavelength, small fluctuation of temperature. Also it could be caused by misalignment of input and output SMFs.

From fitting function it is possible to determine sensitivity of the proposed structure. The period of interference pattern changes the value 0.027 nm when the length of air arm changes about 1 µm. So the resolution is 0.027 nm/µm.

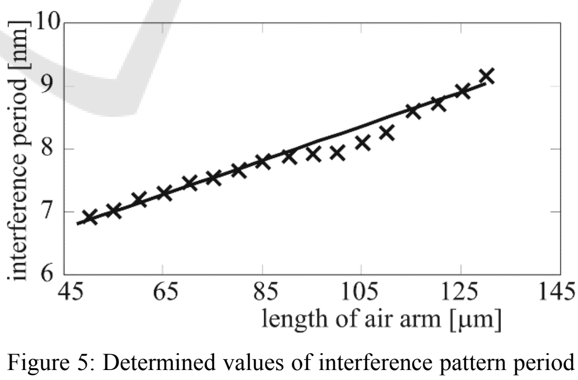

Figure 5: Determined values of interference pattern period for particular length of air arm and its fitting function.

5 CONCLUSIONS

We prepared and demonstrated an optical structure consists of conventional single-mode optical fibres connected by bend optical PDMS microfibre. The optical structure forms Mach-Zehnder interferometer with variable lengths of air arm. The wavelengths and distances of maximums and minimums of the transmitted interference spectra depends on length of air arm. For the operation of the sensor a broadband light source can be used and an optical spectral analyser. For determination of displacement we used a change of the period of interference pattern. The sensitivity of proposed structure is 0.027 nm/μm. The sensitivity could be improved by determination of a phase of interference pattern instead of a period. An advantage of such interferometer is its adjustable air optical line. Such interferometer could be used in applications where the measurands will only affect the properties of microfibre (for example for sensing of volatile organic compounds). A disadvantage of the optical structure is its sensitivity to many physical quantities.

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