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Foil-integrated 2D optical strain sensors

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Abstract

We present two novel approaches to 2D optical strain sensing in thin polymer foils that allow for mass-production by MEMS production techniques. The sensor principles are based on purely optical methods: the sensitive detection of either wavelength or intensity transfer functions in specifically designed planar waveguide structures. The goal is to develop 2D strain sensor arrays that are easy to integrate in flexible polymer foils and which can be applied to a wide range of measurement applications in research and technology. We discuss the sensor concepts and analyze their performance under optimal conditions.

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Keywords: Optical strain sensing; polymer optics; structural health monitoring

1. Introduction

Novel concepts for planar optical strain measurement can be of interest for a range of new applications, such as structural health monitoring for buildings and aircraft or process monitoring in production environments and life science. Such systems can be an alternative to optical fiber sensors with potential benefits regarding flexibility, integration and cost.

In this paper, we propose two approaches for optical strain sensing in one and two dimensions. Current widely used systems for strain sensing are based on electrical principles and are utilized, for example, in structural health monitoring. Recent research on such systems includes, e.g., the application of carbon nanotubes for signal generation [1]. Among the optical systems developed so far, sensors based on Fiber Bragg gratings are most prominent [2]. Both electrical and optical approaches have already been demonstrated for 1D strain sensing

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applications but require relatively expensive readout equipment such as amplifiers for the case of resistance strain gauges or optical spectrum analyzers for the readout of Fiber Bragg sensors.

With the approaches presented in this work we aim at the development of highly-functional strain sensor systems that are accessible to high rate manufacturing techniques based on MEMS (Micro-Electro-Mechanical Systems) production processes, can be integrated in thin polymer foils, and that can be read out with inexpensive equipment. Such systems open the possibility to monitor strain introduced into very flexible structures or structures that are exposed to electromagnetic noise or strong electric and magnetic fields.

2. Two approaches to 1D displacement sensing

One of the simplest solutions to measure any kind of mechanical displacement, i.e. strain, is to couple light from one waveguide into another by placing them in front of each other (butt-coupling). In case that the distance between the two waveguides increases, the coupled power will vary, usually decrease, which can be monitored using a photodiode (see figure 1).

The performance of this type of displacement sensor can be improved by using a lensed waveguide for illumination that focuses the light in front of the detection waveguide. When the detector waveguide is moved out of the focal spot of the illumination waveguide, a decrease in the coupled power will occur, thus, enabling the sensor to detect both elongation and compression. The readout of an array of strain sensors with different distances between illumination and detection waveguides enables determination of the direction and magnitude of elongation and, therefore, of the strain of the underlying substrate [3].

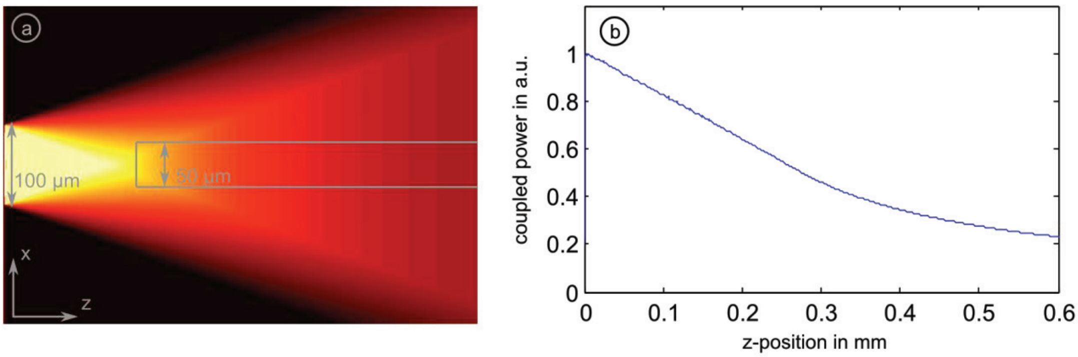

Fig. 1. (a) Light intensity distribution behind a flat-end waveguide; (b) Normalized power coupled to the sensor waveguide as function of the distance between sensor and illumination waveguide.

The second approach to strain sensing utilizes the diffraction of white light on a diffractive optical element, in our case a grating, and determines the induced strain by measuring the wavelength of the light transmitted through planar polymer waveguide arrays. Figure 2 shows a schematic of a possible realisation of such a sensor.

The sensor consists of a rib waveguide (with width wwg = 50 µm and height hwg = 50 µm) guiding the white light and a diffraction grating. The grating diffracts the incoming light into several diffraction orders, see also [4]. The +1st diffraction order is monitored by a second rib waveguide of same dimension. If strain is induced perpendicular to the illumination direction, the grating period p and the slit width s are altered, thus changing the diffraction angle. If the size of the detector waveguide is suitably small a change in the coupled spectrum can be measured by using e.g. a fiber-coupled CCD spectrometer.

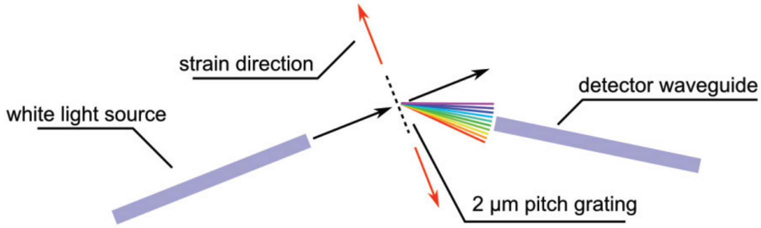

Fig. 2. Schematic of the chromatic strain sensor. A grating is illuminated by an illumination waveguide (left) and the +1st diffraction order in monitored by a sensor waveguide (right). The strain is induced in the direction of the red arrows, altering the grating period p and slit width s.

3. Geometric layout and sensitivity

We chose polymethylmethacrylate (PMMA, nPMMA = 1.49) for the waveguide substrate and Cyclic olefin copolymer (COC, nCOC = 1.53) for the rib waveguide structure, similar to our work in [3], which leads to waveguides with a numerical aperture of NA = 0.348.

The mechanical grating period is set to p = 2 µm and the slit width to s = 1 µm. The illumination spectrum of the white light source is assumed ideal for 380 nm ≤ λ ≤ 780 nm, i.e. for visible light. It is then possible to calculate the angle θ+1 of the m = +1st diffraction order for both minimum and maximum wavelength to

$$\theta_{+1,380} = \operatorname{asin}\left(m\frac{\lambda}{n_{PMMA}\cdot d}\right) = \operatorname{asin}\left(+1\cdot\frac{380\cdot 10^{-9}\mathrm{m}}{1.49\cdot 2\cdot 10^{-6}\mathrm{m}}\right) = 7.33° \tag{1}$$

and

$$\theta_{+1,780} = 15.17°. \tag{2}$$

A possible overlap of the +1st and +2nd diffraction order can be prevented when suppressing the +2nd diffraction order by choosing the slit width to $s = 0.5\cdot p$. The angle α1 between the optical axes of the illumination and the detection waveguide is selected to $\alpha = 11.25°$, i.e. centred within the +1st diffraction maximum (see figure 3).

From the width of the detection waveguide it is possible to determine the value for the lower and upper wavelength of the transmitted light, by geometrical considerations. Positioned at a distance $d_2 = 1$ mm from the grating the detector waveguide covers an angle of

$$\alpha_{\mathrm{det}} = 2\cdot\operatorname{atan}\left(\frac{w_{wg}}{2\cdot d_2}\right) = 2.8642°. \tag{3}$$

Similar to the above calculation, the values for the minimum and maximum wavelength coupled to the detection waveguide can be calculated to

$$\lambda_1 = \sin(\theta_1)\cdot\frac{n_{PMMA}\cdot p}{m} = \sin\left(\alpha - \frac{\alpha_{det}}{2}\right)\cdot\frac{n_{PMMA}\cdot p}{m} == 508.14\ \mathrm{nm} \tag{4}$$

and

$$\lambda_2 = \sin(\theta_2)\cdot\frac{n_{PMMA}\cdot p}{m} == \sin\left(\alpha + \frac{\alpha_{det}}{2}\right)\cdot\frac{n_{PMMA}\cdot p}{m} == 654.23\ \mathrm{nm} \tag{5}$$

as indicated in figure 3.

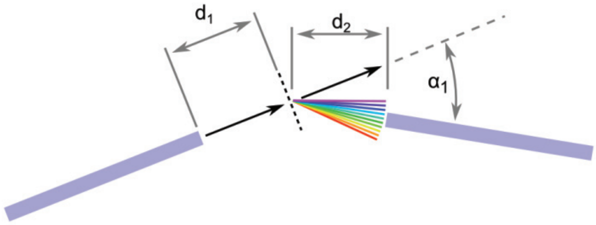

Fig. 3. Dimensions of the chromatic strain sensor. d_1 is 1 mm which ensures both a sufficient number of slits to be illuminated and minimal light losses into the substrate. α_1 is the angle between the optical axis and the detector waveguide placed in the centre of the +1st diffraction maximum. The distance d_2 influences the intensity coupled into the detector waveguide and the spectral width of the transmitted spectrum.

A relative elongation of the strain sensor of 1 ‰ in the direction indicated by the red arrows in figure 2 would change the grating period to $p = 2.002$ µm while the width of the detector waveguide is changed to $w_{\text{wg, strained}} = w_{\text{wg}} \cdot 0.001 \cdot \cos(\alpha_1) = 50.0048$ µm. Repeating the above calculation for this case the minimum and maximum wavelengths of the transmitted spectrum are changed to

$$\lambda_1 = 508.64 \text{ nm} \tag{6}$$

and

$$\lambda_2 = 654.89 \text{ nm.} \tag{7}$$

The wavelength shift amounts to 0.5 nm when the sensor is strained by 1‰ and, therefore, lies well within the spectral resolution of commercial CCD spectrometers [5]. The sensitivity could be further improved by monitoring the shift of the centre of mass of the spectrometer output.

4. Manufacturing and 2D strain sensing

Since both sensors are planar and easy to integrate in polymer foils, it is possible to stack different layers in order to achieve 2D strain sensing. However there is a possibility to combine both concepts – the intensity and the chromatic concept - for a 2D strain sensing without the need of stacking.

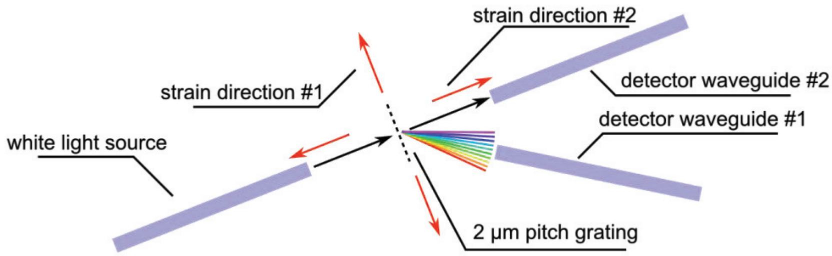

Fig. 4. Combined setup for measurement of strain in two dimensions.

Figure 4 shows a schematic of a combined setup with two detection waveguides, each of them monitoring a separate direction of strain. While detector #1 monitors the strain perpendicular to the optical axis of the illumination waveguide, based on the chromatic concept, detector #2 monitors the intensity of the non-diffracted 0th order. Since strain induced along direction #2 will not change the grating period p, the monitored power in detector waveguide #2 is not coupled to the transmitted spectrum in detector waveguide #1.

We propose hot embossing as a suitable manufacturing process for both sensors and consider PMMA as substrate material which is structured. The structures will be filled with heat-curable acrylate and then covered with another

PMMA layer. The hot embossing process ensures a good scalability as well as the possibility for high rate production using MEMS techniques. While it is, in principle, possible to also process polymer stacks by hot-embossing [6] the production is also scalable by switching to roll-to-roll processes, as described in [7]. For first laboratory demonstrators, however, we plan to use polydimethylsiloxane (PDMS) stamps, as detailed in [3], to produce the rib waveguide array structures required. A grating that is perpendicular to the substrate plane can be manufactured by micro-chiseling with diamond tools on a micromachining centre [8].

For this purpose, a Kugler Micromaster 5X micromachining centre will be used which allows a positioning and manufacturing accuracy of smaller than 1 µm. Note that the limiting factor in the production of such microstructures is the edge radius of the tools used. With carbide tools, the edge radius is limited by the grain size of the carbide material and the smallest radii range from 2 µm down to 0.8 µm [9]. With diamond tools, edge radii down to 0.6 µm are possible [9] and we will investigate the production of gratings in non-ferrous mould-materials in the future.

5. Conclusion and Outlook

In this paper, we have presented two possible approaches for strain-sensing based on planar polymer optics. The intensity sensor approach is based on polymer waveguide arrays in butt-coupling configuration and exploits the fact that the coupling efficiency decreases when the distance between illumination waveguide and detector waveguide increases.

The chromatic sensor approach monitors the 1st diffraction maximum of an illuminated diffraction grating and is able to sense relative elongations of the sensor of approximately 1 ‰ by using a commercial CCD spectrometer. Both concepts can be combined for 2D strain measurement with, in principle, little or no cross-talk between the two strain directions.

In near future we will manufacture the proposed devices by using hot-embossing techniques. Optical characterization and comparison with the simulations will be required to quantify the device performance and to evaluate inaccuracies of the production process. As part of the optical characterization a comparison of the sensors performance to that of existing devices will be carried out. We will also study the performance and durability of the system under harsh environments.

Acknowledgements

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