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# Comparison of different polymers and printing technologies for realizing flexible optical waveguide Bragg grating strain sensor foils

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## ABSTRACT

Waveguides with Bragg gratings realized on a flat polymer foil are promising candidates for advanced strain sensors since such a planar approach allows precise positioning of multiple sensors in various well-defined directions, in the same foil. As such, an optical version of an electrical strain gage can be realized. Herein, several parameters are discussed which define the behaviour of such sensor foils, in particular the grating design, including the wavelength of operation and mechanical and optical properties of the used polymers. Epoxy and Ormocer®-based Bragg grating sensors operating at 850 nm and 1550 nm wavelength were realized using nano-imprint lithography and laser direct-write lithography and their strain and temperature sensitivities were compared. Finally, it is demonstrated that optical strain gage rosettes can be realized by multiplexing 3 angularly displaced sensors in the same waveguide on a single foil.

**Keywords:** Bragg grating sensors, epoxy, foil, imprinting, nano-imprint lithography, optical sensor, Ormocer®, polymer, strain sensor, temperature sensor.

## 1. INTRODUCTION

For monitoring mechanical structures, strain gages have traditionally been used. However, over the past decades, optical strain sensors realized by inscribing Bragg gratings in an optical fiber, have become a high-end alternative. Such optical fiber Bragg grating sensors (FBGs) can be very small, sensitive and are not susceptible to electromagnetic interference. Furthermore, tens or even hundreds of sensors can be multiplexed in the same fiber, drastically reducing the amount of connections compared to an electrical strain gage. However, fibers are sometimes difficult to handle during the installation, especially when they need to be placed under a specific orientation or when they need to be closely spaced. For this reason, we have previously introduced the concept of using a thin polymeric sensor foil, in which multiple grating sensors can be incorporated, having a well-defined orientation [1]. These sensor foils can be made thin enough so that they can be embedded in materials, such as composites, and are flexible allowing bending them down to small curvature radii and withstanding large elongations. Over the past years, we have investigated a number of sensor variations. Therefore, the goal of the current paper is to make a comprehensive overview and comparison since several parameters define the behaviour of such sensor foils, in particular the grating design, the wavelength of operation and mechanical and optical properties of the used materials.

In this paper, epoxy and Ormocer®-based sensors are compared. First, the parameters that influence the sensor design are explained. Then, two different methods for realizing such sensors are discussed. The choice of the most suitable method is closely linked to the used sensor materials and therefore a detailed description of both methods is given. Finally, the resulting sensor properties are compared and the realization of multi-axial strain gage rosettes is demonstrated.

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## 2. WAVEGUIDE BRAGG GRATING SENSOR DESIGN

A waveguide Bragg grating sensor (WBG) consists of an optical waveguide in which a grating is applied. When light with a broad spectrum propagates through the waveguide, the grating will reflect a particular wavelength, the so-called Bragg wavelength $\lambda_B$, defined by the Bragg equation, i.e. $\lambda_B = 2.n_{eff}.\Lambda$, where $n_{eff}$ is the effective refractive index of the waveguide mode and $\Lambda$ is the pitch of the grating [2]. Since both of these parameters will change when the grating is subjected to temperature changes or elongation, this device can be used as a sensor. The (relative) sensitivity of a Bragg grating sensor is given by the following equation [3]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \eta)\Delta T + (1 - \rho_e)\varepsilon_z, \tag{1}$$

where $\frac{\Delta\lambda_B}{\lambda_B}$ is the relative Bragg wavelength shift, $\Delta T$ the increase in temperature, $\alpha$ is the coefficient of thermal expansion (CTE), $\eta$ the thermo-optic coefficient, $\rho_e$ the photo-elastic coefficient of the sensor material and $\varepsilon_z$ the strain applied on the sensor in the direction of the waveguide. Especially the magnitude of $\alpha$ and $\eta$ can be large in case of polymers, making such WBG sensors very sensitive for temperature detection [4]. The sensitivity to strain is typically more comparable to the strain sensitivity of silica-based Bragg grating sensors as discussed in Section 4.1.

The absolute sensitivity to temperature (in pm/K) or strain (in pm/microstrain) is obtained by multiplying (1) by the operation wavelength, i.e. $\lambda_B$. This means that a longer wavelength yields a higher absolute sensitivity. However, other aspects should also be taken into account when choosing the operation wavelength. Most commercially available Bragg grating sensors are realized in silica fibers, and operating around 1550 nm, since a lot of readout equipment is available at this wavelength and the material loss is low. Polymers typically have the lowest loss around a different wavelength, i.e. 850 nm, and at the same time low cost sources and detectors are available, making this wavelength an attractive choice for realizing sensor patches with an integrated readout system [5]. On the other hand, although losses around a wavelength of 1550 nm are higher for polymers (typically >1 dB/cm [6]), they are still acceptable if the waveguides connecting the sensor are not too long, i.e. on relatively small sensor patches.

The operating wavelength is set by choosing the grating pitch $\Lambda$ for a chosen material and waveguide design with a certain $n_{eff}$. In this paper, polymer WBG sensor foils operating around 1550 nm [1] and 850 nm [7] are discussed.

The polymer waveguides, in which the gratings are defined, are designed so that the mode field diameter (MFD) of the propagating mode is matched with standard single mode silica fibers for the readout. Therefore, both the cross-sectional dimensions and the core-cladding refractive index contrast of the waveguides are tuned, at the same time fixing the $n_{eff}$. Tuning the refractive index contrast is very convenient since the employed material systems allow the core and cladding formulations to be mixed achieving intermediate refractive indexes.

## 3. FABRICATION METHODS

### 3.1 Summary of the complete fabrication flow

Two slightly different fabrication approaches were developed for realizing sensor foils using the 2 material classes which were investigated.

The WBG sensors realized in Ormocer® materials (OrmoCore and OrmoClad, obtained from Microresist Technology [8]) on Polyethylene terephthalate (PET) foil carriers employ only imprinting techniques. Single mode waveguides are defined by imprinting a microchannel with the required dimensions in the polymer undercladding (OrmoClad) after which this channel is filled by spin-coating a polymer core material (OrmoCore). During UV-curing of this core material, gratings are formed at the required locations through a second imprinting step. The whole stack is covered with a protective polymer uppercladding layer (OrmoClad).

The WBG sensors realized in epoxy materials (EpoCore and EpoClad, obtained from Microresist Technology [8]) on PET foils are fabricated using both imprinting and laser direct write lithography (DWL). In this case, the gratings are imprinted in the polymer undercladding layer (EpoClad) and the waveguides are defined in a subsequently spin-coated layer of core material (EpoCore) using DWL. This stack is also covered with a protective polymer uppercladding layer (EpoClad).

## 3.2 Grating fabrication using imprinting

For the imprinting steps, a suitable master mold is fabricated using electron beam lithography (EBL) in case of the fine grating feature or using DWL in case of the waveguide features. Afer realizing such a master, it is replicated in a UV-curable PFPE material to realize a soft stamp. Finally, to realize the gratings in the required polymer material, the soft stamp is rolled over a substrate with a spin-coated polymer layer and after a UV curing and baking step the structures are imprinted in this polymer material.

Several variations on the grating imprinting process were investigated over the past years, however only the final, most reliable process is described in detail below and illustrated in Figure 1.

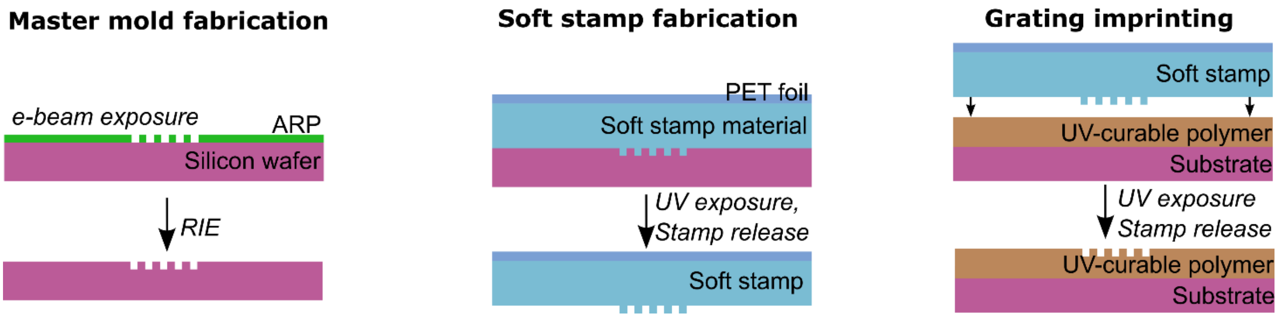

Figure 1. Schematic representation of the process for realizing gratings using imprinting.

***Master mold fabrication***

The grating master mold is realized using e-beam lithography (Raith Voyager). A 250-nm-thick layer of positive e-beam resist ARP 6200.09 (Allresist) is spin-coated on a Si wafer (1500 rpm, 60 s) and soft baked at 150°C for 60 s. Then, a coating, Elektra 92 (Allresist), is spin-coated (2000 rpm, 60 s) to prevent the sample from charging in the e-beam machine. The grating is written with a 50-kV-electron beam in LC30 mode with three different doses: 125, 130 and 135 $\mu C/cm^2$ to select the ideal exposure conditions for this resist. Before developing the sample in AR 600-546 (Allresist) for 60 s, the sample is rinsed with DI water to remove the anti-charging coating. The three different gratings, written with different e-beam doses, are compared qualitatively under the microscope to select the best grating design. The grating with lowest dose appeared not developed through, while the grating with highest dose appeared overdeveloped. Therefore, the gratings written with a dose of 130 $\mu C/cm^2$ were selected for realizing the sensors.

After developing, the grating is transfered into the Si substrate using a reactive ion etcher (Vision 320 RIE, Advanced Vacuum) to fabricate a reliable master. This is done in three steps: a first step to remove the remaining resist in between the grating lines, a second step to etch 100 nm of Si and a third step to strip the resist after etching. In Table 1, the parameters used during these three etching steps can be found. Figure 2 shows a microscope image of the etched grating together with SEM micrographs of the grating seen from the top and in cross-section (realized using focussed ion beam (FIB)).

Table 1: Parameters used for reactive ion etching of silicon gratings using e-beam patterned ARP resist.

| | | **Time [s]** | **Gas and flow rate** | **Pressure [mtorr]** | **Power [W]** |
|---|---|---|---|---|---|
| **Step 1** | Residue removal | 10 | 25 sccm $O_2$ | 20 | 75 |
| **Step 2** | Si etching | 120 | 100 sccm $CF_4$,<br>4 sccm $H_2$,<br>2 sccm $SF_6$ | 20 | 200 |
| **Step 3** | Resist removal | 180 | 50 sccm $O_2$ | 100 | 75 |

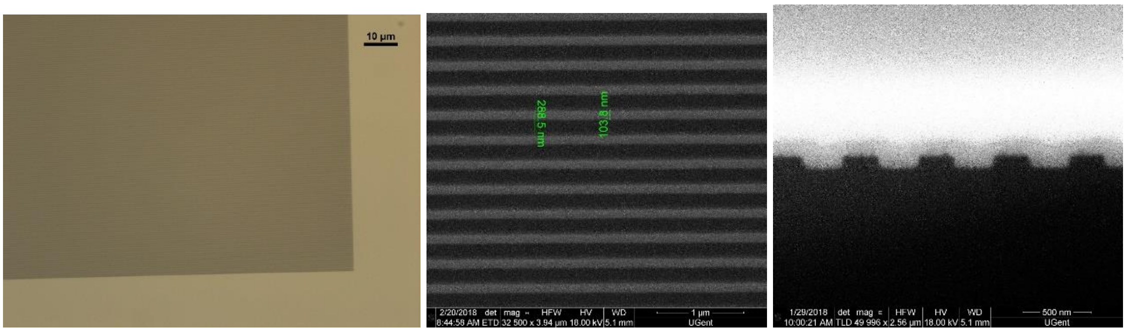

Figure 2. Microscope image, SEM micrograph top view and SEM micrograph cross-section (realized using a focused ion beam) of an etched grating in Si.

***Soft stamp fabrication***

Soft stamps are fabricated by replicating the master molds into a UV curable transparent perfluoropolyether (PFPE) polymer. This polymer is prepared by adding 3 % Irgacure 2022 photoinitiator (BASF) to Fomblin MD 700 (Solvay) by weight. After manually mixing thoroughly, the viscous mixture is let to rest for 1 hour for degassing. Meanwhile, anti-sticking layer is applied on the master to avoid that PFPE material remains between the grating lines of the Si master after releasing. Subsequently, the mixture is spin coated (500 rpm, 30 s) on the master mold and covered using a PET tape with the sticky side touching the spin-coated layer. This stack is UV exposed (365 nm, 30 mW/cm$^2$, 60s) and peeled off from the master mold once cured. This flexible soft stamp can now be used to imprint the gratings in the polymer material.

***Grating imprinting in Ormocer® and epoxy materials***

Gratings in the required polymer material are realized by replicating the structures from the soft stamp. Therefore, a layer of the UV-curable polymer is spin-coated and soft-baked if needed. Afterwards, the soft stamp is brought in contact via a rolling motion to avoid trapped air and the stack is exposed to UV light. Finally, the stamp is peeled off and the polymer is further cured during a baking step. For realizing Bragg grating sensors, the gratings are fabricated at the core-cladding interface of a waveguide. The gratings can therefore be imprinted either in the polymer cladding or core material, as explained in Section 3.4 and 3.5.

### 3.3 Single mode waveguide fabrication

For the epoxy-based sensors, the waveguides are realized using laser DWL technology, as described in [6], since this is a standard, and flexible technology. Furthermore, by optimizing the DWL process, it is possible to write high-quality waveguides on top of grating structures in an underlying (cladding) layer. Using standard mask lithography, employing non-monochromatic and non-perfectly collimated light, this is much more difficult due to diffraction at the mask and grating features. This usually leads to poorly defined waveguide structures.

For the Ormocer®-based sensors, the waveguides are realized using imprinting since the material was not compatible with the available DWL system. The process for imprinting waveguides is conceptially the same as for imprinting gratings. Apart from the different master which is required, the most important difference is that the process needs to be optimized to avoid a residual layer which could cause light to leak out from the waveguide.

The master mold for the waveguides is fabricated having microchannels with the required dimensions. Since the optical waveguides in Ormocer® and operating around λ = 1550 nm require cross-sectional dimensions of 3x4 µm$^2$, standard lithography is used. Therefore, a 3 µm thick EpoCore_2 negative resist (MicroResist Technology) layer is spin-coated (2000 rpm, 30 s) on a cleaned 4” silicon wafer. After a soft baking step (2 min at 50 °C and then 4 min at 90 °C), a photomask having 4 µm wide lines is brought in contact with this layer and UV-exposed with a dose of 200 mJ/cm$^2$. After a post baking step followed by a developing step (mr-Dev 600), approximately 4 µm wide and 3 µm deep channels remain in the resist. For Ormocer® waveguides operating around λ = 850 nm, a similar master mold is realized, but with 3 µm wide and 3 µm deep channels in the resist. The soft stamp is realized in the same way as described above for the grating stamps. Also the process for imprinting the waveguides is similar as for imprinting gratings. To minimize the residual layer, the thickness of the Ormocer® layer in which the waveguides are imprinted is precisely controlled by adding a suitable amount of maT-1050 thinner solvent before spin-coating, and the design of the master mold can be optimized. As such, residual layers as thin as several hundreds of nanometers can be achieved [7, 9].

### 3.4 Ormocer® sensor fabrication

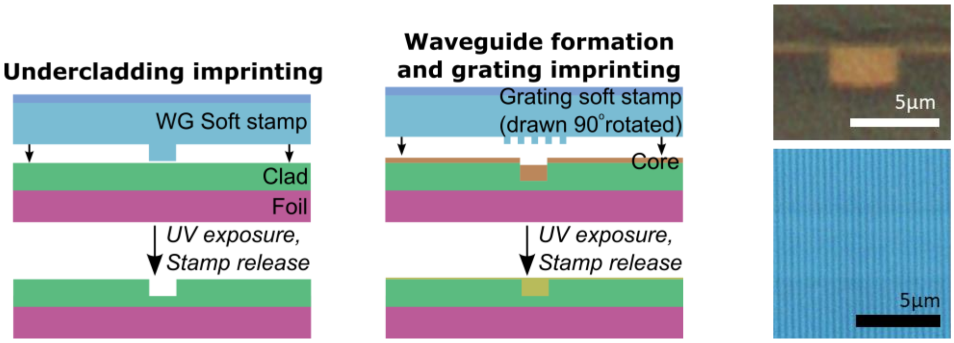

Figure 3. Schematic illustration of the Ormocer® sensor fabrication process (left), typical cross-section of an imprinted waveguide (top right) and top view image of gratings imprinted at the top surface of a waveguide (bottom right).

This section describes the complete fabrication flow for realizing the Ormocer® sensor foils making use of the basic fabrication steps as described above, see also Figure 3.

First, a 18 µm-thick OrmoClad layer is spin-coated on a PET foil (PMX739, 175 µm thick, Hifi film) which is first plasma treated (Diener Pico, 190 W, 40 kHz generator, 24 s, 0.8 mbar, gas used: air). The flexible soft stamp with waveguide channels is rolled over the undercladding layer to avoid air being trapped in the channels. This stack is UV exposed in an $N_2$ environment as the material layer does not cure in an oxygen-rich environment. After curing, the soft stamp is peeled off and can be used again. The cladding layer is then baked in a convection oven to complete the polymerization process.

For the core layer, a 1:2.5 OrmoCore:maT-1050 (Microresist Technology) mixture is made by weight. This ratio is chosen to achieve a thin layer that just fills the channels after imprinting. The mixture is spin-coated on the plasma treated (Diener Pico, 190 W, 40 kHz generator, 24 s, 0.8 mbar, gas used: air) microchannel layer and the solvent is evaporated during a subsequent soft-bake step. Then, the second soft stamp with the grating structures is applied manually in a rolling motion on the OrmoCore layer ensuring that the gratings are well aligned with the waveguides. To facilitate this manual alignment, large 1 $cm^2$ grating islands are used. This step imprints the grating sensors at the top surface of the waveguides, and at the same time ensures the capillary filling of the channels with the core material. The spin-coating thickness is optimized to have as little residue as possible between the channels while having enough material to completely fill the channels. While the stamp is in place, a UV exposure is applied in a $N_2$ chamber to cure the OrmoCore material. After removing the stamp, the layer is baked in an oven and a uniform uppercladding layer is applied using the same parameters as for the undercladding layer, but without imprinting using a stamp. As such, a 3x4 $\mu m^2$ waveguide with integrated grating sensors is achieved, which is completely surrounded and protected with cladding material. The used parameters are detailed in Table 2. For Ormocer® waveguides operating around λ = 850 nm, a 1:1 mixture (by weight) of OrmoCore:OrmoClad is used as cladding material to achieve the required refractive index contrast. The rest of the fabrication process is analogous.

Table 2: parameters used for realizing the Ormocer® sensor foils operating around λ = 1550 nm.

| | **Cladding layers** | **Core layer** |
|---|---|---|
| **Material** | OrmoClad | 1:2.5 OrmoCore:maT-1050 |
| **Spin-coating parameters** | 30” @ 3000 rpm | 30” @ 3000 rpm |
| **Resulting layer thickness** | 18 µm | 3 µm |
| **Soft baking** | Not required | 5’ @ 100 °C on a hotplate |

| | | |
|---|---|---|
| **Imprinting** | Manually @ room temperature | Manually @ room temperature |
| **UV flood exposure** | 10” @ 30 mW/cm$^2$ in a $N_2$ chamber | 15” @ 30 mW/cm$^2$ in a $N_2$ chamber |
| **Post baking** | Not required | 5’ @ 100 °C on a hotplate |
| **Hard baking** | 90’ @ 120 °C in a convection oven | 90’ @ 120 °C in a convection oven |

## 3.5 Epoxy sensor fabrication

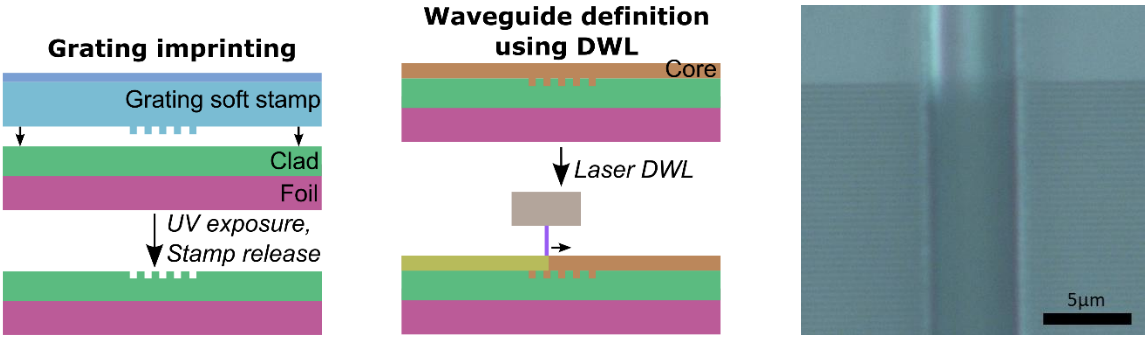

Figure 4. Schematic illustration of the epoxy sensor fabrication process (left) and top view microscope image of the resulting waveguide written on top of gratings imprinted in the cladding (right; microscope focus is on the gratings).

This section describes the complete fabrication flow for realizing the Epoxy sensor foils making use of the basic fabrication steps as described above, see also Figure 4.

The undercladding layer, EpoClad_50 (Microresist Technology), is spin-coated on a plasma treated PET foil (Diener Pico, 190 W, 40 kHz generator, 24 s, 0.8 mbar, gas used: air) and baked on a hotplate to evaporate the solvent. The flexible soft stamp with gratings is rolled over the undercladding layer on a hotplate. The imprinting has to be done at elevated temperature to soften the material and make sure that the material fills the spacing between the grating lines. The imprinted gratings are then cured with UV light. Afterwards the soft stamp is peeled off and can be used again. Another baking step on a hotplate and in a convection oven follows.

EpoCore_5 (Microresist Technology) is used as core material and spin-coated on the plasma treated EpoClad layer with gratings. The solvent is evaporated by baking it on a hotplate. The waveguides are now written employing laser DWL (Heidelberg DWL66; 477 mJ/cm$^2$, $\lambda$ = 355 nm). The sample is placed on a hotplate again before it is developed in mr-Dev 600 (Microresist Technology) for 50 s and rinsed with IPA. To finalize the polymerization process the sample undergoes one more baking step in a convection oven.

After a post-baking step followed by a developing step (mr-Dev 600) and another baking step in a convection oven, the uppercladding layer, EpoClad_50, is applied following the same parameters as the undercladding layer, but without the imprinting step. The used parameters are detailed in Table 3.

Table 3: parameters used for realizing the epoxy sensor foils operating around $\lambda$ = 1550 nm.

| | **Cladding layers** | **Core layer** |
|---|---|---|
| **Material** | EpoClad_50 | EpoCore_5 |
| **Spin-coating parameters** | 60” @ 5000 rpm | 30” @ 3200 rpm |
| **Resulting layer thickness** | 16 µm | 5 µm |
| **Soft-bake (on a hotplate)** | 5’ @ 50 °C; 5’ @ 90 °C; 15’ @ 120 °C | 3’ @ 50 °C; 5’ @ 100 °C |
| **Structure definition** | Using imprinting @ 90 °C | Using laser DWL |
| **UV exposure** | Flood exposure, 40” @ 30 mW/cm$^2$ | DWL: 477 mJ/cm$^2$, $\lambda$ = 355 nm |

| | | |
|---|---|---|
| **Post-bake (on a hotplate)** | 15’ @ 85 °C | 3’ @ 50 °C; 5’ @ 90 °C |
| **Develop** | Not required | 50” in mr-Dev 600, 1’ IPA |
| **Hard bake** | 90’ @ 120 °C in a convection oven | 90’ @ 120 °C in a convection oven |

## 4. COMPARISON OF THE RESULTING SENSOR PROPERTIES

### 4.1 Sensor sensitivities

The temperature sensitivities were determined by recording the Bragg wavelength while the sensor was heated to different temperatures, using a thermocouple as a reference. The strain sensitivities were determined employing tensile tests. More details on the sensor characterization methods can be found in [1, 7]. Table 4 gives an overview of the realized sensors and their temperature and (axial) strain sensitivity. Note the longer operating wavelength of the epoxy sensors for the same grating pitch because of the higher material refractive index (and hence $n_{eff}$).

All sensors show a negative temperature sensitivity, meaning that the Bragg wavelength undergoes a blue-shift when temperature increases. This is caused by the highly negative thermo-optic coefficient of the used materials. For OrmoCore and OrmoClad, the thermo-optic coefficient is about -250 ppm/K and -270 ppm/K respectively and for EpoCore and EpoClad about -70 ppm/K according to data of the manufacturer [8]. This explains the lower temperature sensitivity of the epoxy sensors as compared to the Ormocer® sensors. However, as discussed above, the exact sensitivity also depends on the thermal expansion coefficient (CTE) of the sensor material (about 100 ppm/K for OrmoCore and OrmoClad and about 87 ppm/K for EpoClad [10]) but may also depend on the substrate on which the sensor is realized, since this may prevent or promote the sensor grating to expand when temperature increases. The epoxy and Ormocer® sensors with a grating pitch of 505 nm compared in Table 4 were realized on a glass fiber reinforced epoxy substrate (FR-4), while the Ormocer® sensor with a grating pitch of 280 nm was realized on a 175 µm thick PET foil.

Comparing the Ormocer® sensors with different grating pitch confirms the lower (absolute) sensitivity at shorter operating wavelengths, as dictated by equation (1). However, the obtained sensitivity does not scale exactly with the wavelength, which would be expected if the optical material constants are not wavelength dependent. This also indicates the influence of the substrate on the sensitivity.

The difference in axial strain sensitivity between the Epoxy and Ormocer® sensor with $\Lambda$ = 505 nm is rather small (about 10 %), meaning that the photo-elastic coefficients of both materials are only slightly different. Comparing the Ormocer® sensors with different grating pitch again shows that the sensitivity does not scale perfectly with the wavelength, which could indicate that the photo-elastic coefficient of this polymer is wavelength dependent. Unfortunately, very little data is available about photo-elastic coeffients of polymers so that more research is required to confirm this hypothesis.

Table 4: Overview of the realized sensors and their sensitivities.

| Material | $\lambda_B$ (nm) | $\Lambda$ (nm) | $n_{eff}$ (-) | Temperature sensitivity (pm/K) | Axial strain sensitivity (pm/microstrain) |
|---|---|---|---|---|---|
| **Epoxy (EpoCore and EpoClad)** | ~ 1580 | 505 | 1.564 | -90 | 1.27 |
| **Ormocer® (OrmoCore and OrmoClad)** | ~ 1540 | 505 | 1.525 | -250 | 1.41 |
| **Ormocer® (OrmoCore and OrmoClad)** | ~ 860 | 280 | 1.535 | -150 | 0.85 |

### 4.2 Other differences between the sensors

Apart from the different processing requirements and sensitivities of epoxy sensors compared to Ormocer® sensors, there are other elements which may favor the selection of a certain sensor material.

Using both materials, sensors can be realized on various types of rigid substrates (glass, silicon, FR-4) and also on thin and flexible PET foils. Especially for realizing strain sensors, the sensors should be flexible. However, to ensure a reliable sensor fabrication process, the foil substrate cannot be chosen too thin (currently the chosen foil thickness was 175 µm). Even thinner sensor foils (down to 50 µm thick) can be realized by releasing the functional sensor stack from a temporary carrier after the fabrication [11]. However, Ormocer® sensors are very brittle after releasing, making them very difficult to handle as freestanding sensors. The epoxy sensors do not suffer from this and are easy to handle after releasing. This makes epoxy sensors ideally suited in case very thin foils are required, for example when the sensors are integrated inside composite materials [1].

### 4.3 Multi-axial sensors

The Bragg grating sensor principle allows multiplexing several grating sensors in the same waveguide. This allows reading out multiple sensors using a single optical interconnection. Therefore, the grating pitch of each sensor should be chosen slightly differently, so that a different Bragg wavelength is reflected by each sensor. Furthermore, because of the planar sensor foil approach, the orientation of the sensors can be tuned and precisely defined during the fabrication. This enables for example realizing an optical variant of an electrical strain gage rosette in a very compact way. With such a sensor rosette, the general internal strain state of a mechanical structure can be monitored, regardless of the orientation of the foil. This was demonstrated by imprinting 3 gratings closely together but angularly displaced by 45°and with slightly different pitch in a waveguide having two times a 45° bend, see Figure 5. Using this approach, a 45° sensor rosette in Ormocer® material both operating around 1550 nm [1] and around 850 nm [7] and recently also a sensor rosette in epoxy operating around 1550 nm was realized. Although the latter sensor foil is still under characterization, the expected reflection spectrum was seen after the fabrication. This shows that both the imprinting based fabrication method using Ormocer materials and the DWL based fabrication method using epoxy materials can be scaled towards the integration of multiple sensors in a single foil.

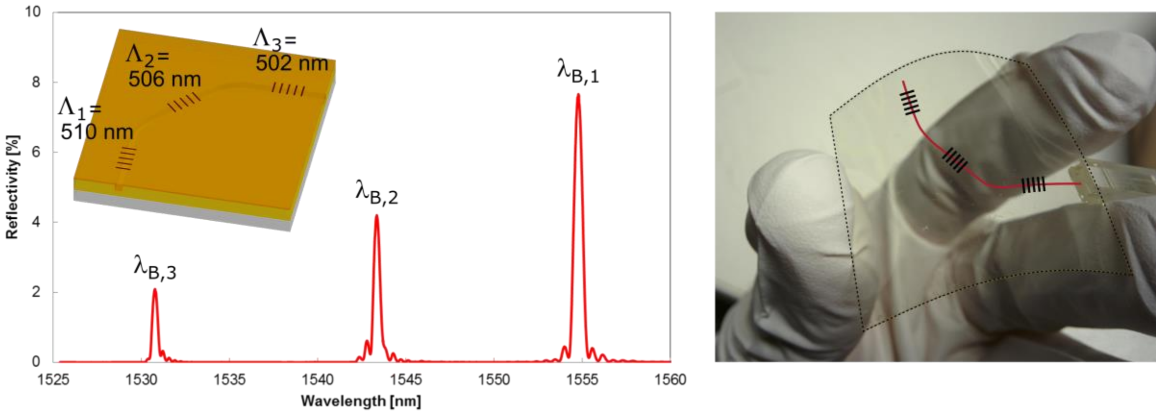

Figure 5. Reflection spectrum of a multi-axial, Ormocer®-based sensor and photo of the sensor foil with orientation of the waveguide and gratings highlighted.

## 5. CONCLUSIONS

The WBG sensor technology is interesting because it enables realizing very thin foils with multiple multiplexed, closely spaced optical sensors under well-defined orientations. Furthermore, by selecting the polymer sensor materials and tuning the grating design, the sensor properties can be tailored. This was demonstrated by comparing different sensors realized in epoxy and Ormocer® materials. The Ormocer® sensors show the highest temperature sensitivity (-250 pm/K at $\lambda$ = 1540 nm), while the epoxy sensors can be realized as freestanding, ultra-thin foils (50 µm) allowing them to be unobtrusively integrated in or on mechanical structures. Strain sensitivities are rather similar for both materials, with the sensitivity of the Ormocer® sensors being slightly higher (1.41 pm/microstrain) compared to the sensitivity of epoxy sensors (1.27 pm/microstrain) operating both around 1550 nm.

It was also highlighted that both materials require a slightly different fabrication processes, especially for the definition of the single mode waveguides. The fully replication-based fabrication process for realizing the Ormocer® sensors is interesting from a low-cost high-volume fabrication point of view. On the other hand, the laser DWL technology for realizing the waveguides of the epoxy based sensors, is a very flexible technique, especially during the R&D phase. Both fabrication methods and materials allow realizing sensor foils multiplexing several sensors in the same waveguide.

## ACKNOWLEDGMENTS

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