# Encapsulation of FBG Sensor into the PDMS and its Effect on Spectral and Temperature Characteristics

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***Abstract.*** *Fiber Bragg Grating (FBG) is the most distributed type of fiber-optic sensors. FBGs are primarily sensitive to the effects of temperature and deformation. By employing different transformation techniques, it is possible to use FBG to monitor any physical quantity. To use them as parts of sensor applications, it is essential to encapsulate FBGs to achieve their maximum protection against external effects and damage. Another reason to encapsulate is increasing of sensitivity to the measured quantity. Polydimethylsiloxane (PDMS) encapsulation appears to be an interesting alternative due to convenient temperature and flexibility of the elastomer. This article describes an experimental proposal of FBG PDMS encapsulation process, also providing an analysis of the FBG spectral characteristics and temperature sensitivity, both influenced by high temperature and the process of polydimethylsiloxane curing itself. As for the PDMS type, Sylgard 184 was employed. Encapsulation consisted of several steps: allocation of FBG to PDMS in its liquid state, curing PDMS at the temperature of 80 °C ± 5 %, and a 50-minute relaxation necessary to stabilize a Bragg wavelength. A broadband light source and an optical spectrum analyzer were both used to monitor the parameters during the processes of curing and relaxation. Presented results imply that such a method of encapsulation does not have any influence on the structure or functionality of the FBG. At the same time, a fourfold increase of temperature sensitivity was monitored when compared to a bare FBG.*

## Keywords

***Encapsulated, fiber Brag grating, polydimethylsiloxane, spectral characteristic, temperature sensitivity.***

## 1. Introduction

Fiber-optic Bragg gratings are elements whose function is based on periodic changes of refractive index in the core of the optical fiber. Their usage is now widespread within fiber-optic sensor applications. The key areas of concern are physical quantities such as temperature, deformation, pressure, vibration, etc. Optical fibers, which are made of germanium silicate glass, are very strong in tensile, but these fibers have very low resistance to mechanical damage. Currently, we use some types of encapsulation which are designed according to the requirements for the measurements of different physical quantities. The tasks of encapsulation are an additional protection of the fiber with FBG, empowerment of sensitivity on the measured quantity, and minimalized sensitivity to other physical quantities. PDMS elastomer, which exhibits suitable thermal and elastic properties, is a suitable alternative to material for encapsulation of FBG. This elastomer is harmless, nontoxic, non-flammable and electrically nonconductive.

Polyimide, acrylate and ormocer are the basic protections. In addition to these primary protections, we use a number of other encapsulations. For example, the team of authors [1] describes the encapsulation of FBG into a variety of metallic coatings which are used for increasing sensitivity for the measurement of tensile stress. An interesting alternative is the use of nickel. The authors [2] describe achieving an increase of the temperature sensitivity of FBG. The article [3] describes encapsulation of FBG into steel, and the influence of encapsulation on the deformation sensitivity of FBG. Paper [4] describes a 4.2 times increase in the temperature sensitivity of FBG due to the insertion of FBG into PDMS. We have not found the team of authors focused on the issue of encapsulation of FBG into PDMS, and the impact of encapsulation on the parameters of FBG. So the aim of the authors was to analyse the impact of high temperature and to cure PDMS on spectral characteristics and temperature sensitivity of FBG. Sylgard 184 was chosen as a product that exhibits excellent heat resistance, excellent elastic properties, harmlessness, nontoxicity, and electric nonconductivity. The actual encapsulation Bragg grating, within PDMS, extends the application potential of FBG sensors, e.g. in the field of medicine.

## 2. Operating Principles

PDMS belongs among polymeric organosilicon compounds, and it is often referred to as silicone rubbers. These compounds contain a bond of Si-O in one molecule. The toughness of silicone rubbers is low, but their advantage is that they remain almost unchanged in a broad range of temperature. Conventional temperature applicability is $-60$ °C to $+200$ °C. PDMS can withstand temperature up to 350 °C for short-term temperature straining. Silicone rubbers can be divided into three groups. These groups are PDMS for general use, the PDMS having phenyl substituents (for improved low-temperature flexibility), and PDMS with 1,1,1- trifluoro propyl substituents (resistant against oils and fuels).

As for its chemical composition, PDMS belongs among optically pure materials. PDMS only contain a small degree of impurities. Therefore, PDMS is not a suitable environment for bacteria. PDMS is a clear liquid which is odorless and tasteless, resistant to chemicals, radiation, UV radiation and high temperatures in hundreds of degrees Celsius (°C). The main disadvantage is the expensive and complicated production. PDMS is used in a broad range of fields such as electronics, medicine, astronautics or automotive industry.

PDMS is produced using technical silicon and a combination of hydrochloric acid and methanol. This combination creates the so-called chloromethane. The production goes through four chemical phases (by synthesis, by rectification, by hydrolysis, by polycondensation). The final chemical composition of polydimethylsiloxane can be seen in Fig. 1. The organic substituent is almost always represented by methyl ($CH_3$).

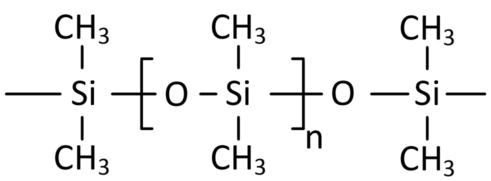


**Fig. 1:** Chemical composition of PDMS.

Sylgard 184 is a designation for a two-component potting and encapsulating elastomer, on the basis PDMS, which is supplemented by a curing agent. PDMS can be cured at the elevated temperature after addition of the curing agent. Sylgard 184 belongs among moderately viscous liquid elastomers. Temperature range of usability is $-55$ °C to $+$ 200 °C. Highlights include an excellent physical resistance to mechanical damage, radiation, and electrical nonconductivity. Sylgard 184 is already cured at room temperature of 25 °C. However, it needs a long period in tens of hours. At the temperature of around 100 °C it is possible to achieve the curing in matter of hours or earlier [5], [6] and [7].

Bragg gratings are the most common type of single-point sensors. They consist of a periodic change of core index in the optical fiber (Fig. 2).

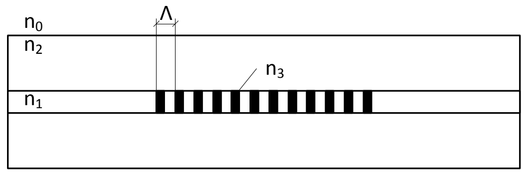



**Fig. 2:** Structure of fiber Bragg Gratings.

The spectral reflection of the specific wavelength, which is called the Bragg wavelength, occurs at these interfaces. Other wavelengths pass through the structure without attenuation. The important parameter which defines the size of the Bragg wavelength is the period of the changes in the refractive index. Bragg wavelength is given by:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where $n_{eff}$ is the effective refractive index, and $\Lambda$ is the period of changes in the refractive index. The used FBG sensor is based on the temperature and deformation sensitivity. The size of the Bragg wavelength, which is dependent on the operating temperature and mechanical strain, can be expressed as:

$$\frac{\Delta\lambda}{\lambda_0} = k\varepsilon + (\alpha_\Lambda + \alpha_n)\,\Delta T, \tag{2}$$

where $\alpha_\Lambda$ is the coefficient of thermal expansion, $\alpha_n$ is temperature-optical coefficient and $k$ is the deformation coefficient defined as:

$$k = 1 - p_e. \tag{3}$$

In Eq. (3), $p_e$ is the photo-elastic coefficient. This coefficient takes the value of 0.21 for standard silica optical fiber G.652.D. Coefficient $\alpha_\Lambda$ is $0.55\cdot10^{-6}$ °C$^{-1}$ and $\alpha_n$ is in the range 6.4–8.6$\cdot10^{-6}$ °C$^{-1}$ [8] for optical fiber G.652.D. Temperature and deformation dependence is caused both by the values of parameters and the central Bragg wavelength. Therefore, we state normalized temperature coefficient for determining of these sensitivities:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta T} = 6.678 \cdot 10^{-6}\ ^{\circ}\mathrm{C}^{-1}, \tag{4}$$

and normalized deformation coefficient:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.78 \cdot 10^{-6}\ \mu\mathrm{strain}^{-1}. \tag{5}$$

Uniform Bragg grating (used in this article) on the wavelength 1554.1203 nm shows temperature sensitivity of 10.378 pm/°C and a strain sensitivity of 1.212 pm/µstrain.

## 3. Experimental Setup

Uniform FBG was used to implement the sensor. This uniform FBG has polyimide protection with the Bragg wavelength of 1554.1203 nm, the width of the reflecting spectrum of 2.3247 nm, and a reflectivity of 95.6 %. This type of FBG is the most used one within the sensorial applications. Encapsulated FBG is used in medical applications (such as pulse, respiration) because this FBG has both tighter polyimide protection for the optical fiber and better transfer of deformation effect on FBG. The experiment is an innovative type of encapsulation. In the experiment, we investigated the effect of temperature, the curing, and the mechanical stress on spectral characteristics of FBG and temperature sensitivity of FBG. A follow-up research will focus on comparing different types of FBG for verifying and extending the application of such encapsulated FBG.

For the experiment we used a two-component (PDMS and curing agent) elastomer Sylgard 184. The chosen ratio of the mixture was 10:1 where the two-component Sylgard 184 comprises 10 parts and the curing agent forms 1 part. The actual implementation of encapsulation consists of three phases. In all the phases of the encapsulation, we monitored the influence of temperature, the curing and the mechanical stress on the spectral characteristics of FBG. Broad-spectrum LED (Light-Emitting Diode) which has a central wavelength of 1550 nm, and an output power of 1 mW, was used as the radiation source. LED was stabilized by temperature and the current controller labeled LDC 202C and TED 202C made by Thorlabs. Therefore, we obtained a stable optical power. The spectral characteristics were monitored using the optical spectrum analyzer OSA203 by Thorlabs with the Wavelength Meter Resolution about 0.1 pm. Values in Tab. 1 have been rounded to two decimal places. Temperature box has the designation of Concept ET 5050. The optical circulator directed the reflected signal from the FBG to the optical spectrum analyzer within the experiment. The used type is "Polarization Insensitive Circulator" with the value of insertion loss port 1 to port 2 0.54 dB and port 2 to port 3 0.68 dB. Figure 3 shows a diagram of the experimental measurement.

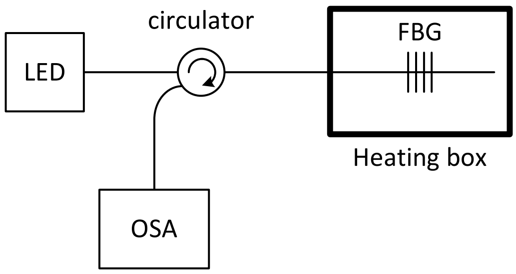



**Fig. 3:** Scheme of measurement with heating box.

Prepared Sylgard 184 with the volume of 25 ml and in the above-mentioned ratio of 10:1, was placed in an ultrasonic bath Ultrasonic Cleaner for 60 minutes. Therefore, we achieved both maximum homogeneity of the mixture and eliminated air bubbles (Fig. 4).

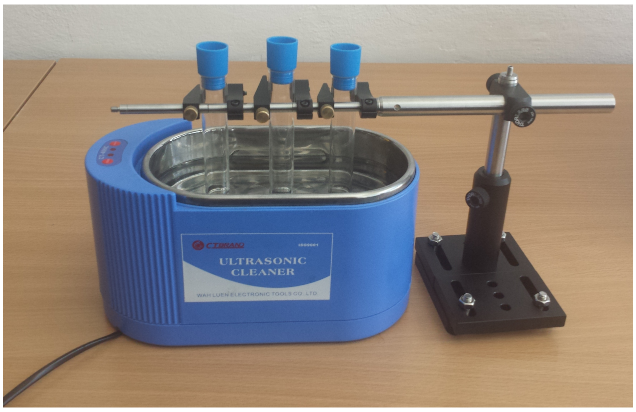



**Fig. 4:** Used ultrasonic bath for preparing Sylgard 184 mixture in the ratio 10:1.

In the first phase, we performed the encapsulation of FBG into PDMS in the liquid state. Figure 5 shows a prepared form, in which the FBG was placed and subsequently encapsulated by liquid PDMS.

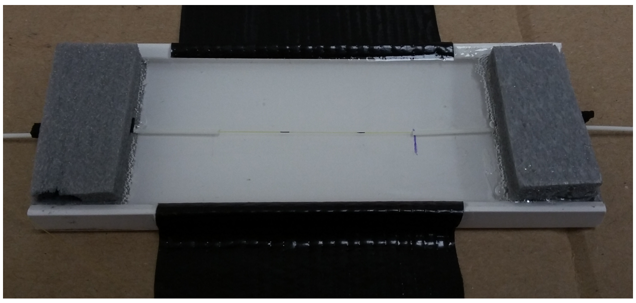


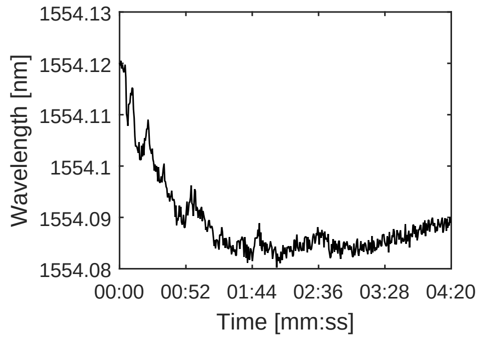
**Fig. 5:** Realization of encapsulation of FBG.

The course of Bragg wavelength change is shown in Fig. 6(a) during potting FBG into liquid PDMS. The next step moved forms with FBG into a preheated thermal cabinet with the temperature of 80 °C. The course of the Bragg wavelength is shown in Fig. 6(b). In the second phase, curing PDMS with the FBG in the temperature box was carried out (Fig. 6(c)). Based on the datasheet, the temperature in the box was set to 80 °C. The temperature was monitored by the thermal cell during curing, and the temperature deviation was 80 °C ± 5 % within the measurement. Figure 6(d) represents the evolution of Bragg wavelength within a 50-minute relaxation.

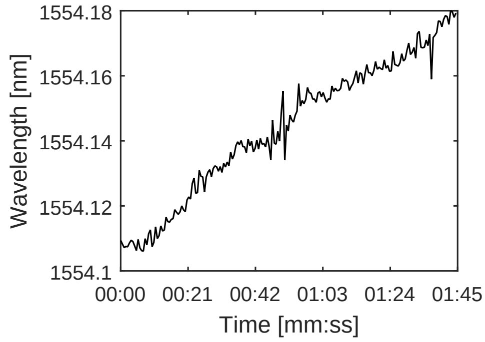
The changes of Bragg wavelength, which are evident in the attached graphs (Fig. 6) can be explained by the influence of temperature, the curing and mechanical stress in handling. The most significant change of Bragg wavelength can be seen in Fig. 6(c), and it represents the time interval 10-15 minutes from insertion FBG in the liquid PDMS into a thermal box with temperature 80 °C. Figure 6(d) represents a relaxation time (50 minutes) at room temperature of 25 °C until stabilization of Bragg wavelength.

During the potting into PDMS and curing we observed rapid increase of Bragg wavelength that was affected by higher temperature (from 25 °C to 80 °C). Initial Bragg wavelength corresponds to the value of 1554.09 nm that was measured after the process of potting had been finished, see Fig. 6(a). Maximal Bragg wavelength (Fig. 6(c)) that we obtained is 1554.66 nm (difference of 570 nm). In this phase only temperature sensitivity for bare FBG is presented with the value of 10.38 pm/°C. This value corresponds to the temperature change of 54.91 °C. Linear growth of Bragg wavelength from 18 min in Fig. 6(c) is caused by low value of thermal conductivity of PDMS material and slow expansion influenced by thermal expansion. In the relaxation phase we indicated sharp reduction of Bragg wavelength because of PDMS material cooling. We observed the high thermal sensitivity of PDMS, which is 4 times bigger in comparison to bare FBG. After the cooling process of PDMS from 80 °C to 25 °C, thermal sensitivity reached 39.44 pm/°C, and the Bragg wavelength reduced to 1552.26 nm. This decline corresponds to the temperature decrease by 57.55 °C.

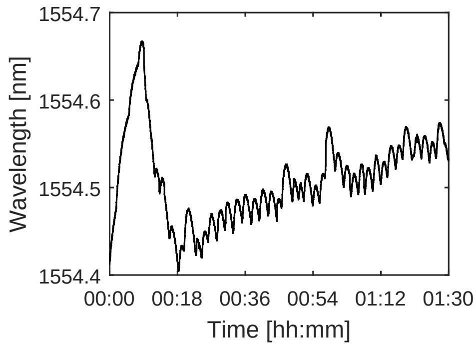
Figure 7 shows the reflective spectral characteristic of the Bragg grating before and after the curing, including the relaxation time of 50 min. The presented results indicate that this type of encapsulation does not affect the structure of the FBG. However, the encapsulation causes a shift of the reflected spectrum of FBG to lower wavelengths due to the shrinkage of PDMS during curing. A shift of the Bragg wavelength was 1.8652 nm. The spectral width of Bragg grating (Full Width Half Max) increased from the value 2.324 nm to 2.386 nm. However, this shift does not affect the functionality of the FBG sensor.



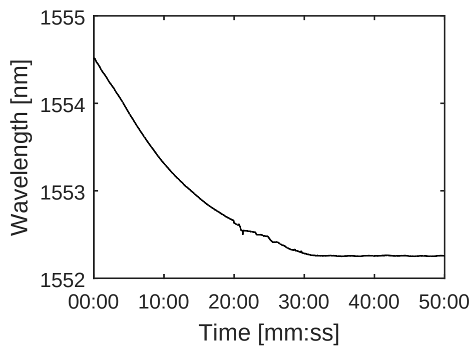

(a) Potting into PDMS.




(b) Inserting into thermal box.




(c) Curing.




(d) 50-minute relaxation.

**Fig. 6:** Spectral characteristics of Bragg grating during encapsulation.

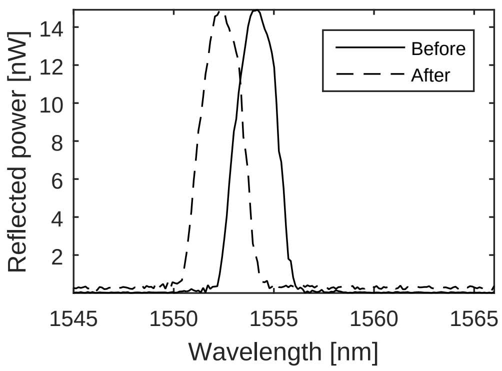



**Fig. 7:** The spectral characteristic of FBG before and after curing.

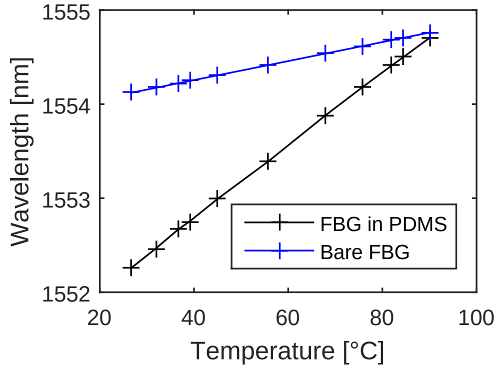



**Fig. 9:** Bragg wavelength dependence of non-encapsulated (blue line) and encapsulated (black line) FBG on temperature.

Table 1 shows the spectral characteristics of FBG in various stages of encapsulation. There are given values of the parameters before and after each phase.

**Tab. 1:** Spectral characteristics of FBG during encapsulation of FBG (all 4 phases).

| **Phases of encapsulation** | **Wavelength [nm]** | |
|---|---|---|
| | Before | After |
| Encapsulating | 1554.12 | 1554.12 |
| Inserting into heating box | 1554.11 | 1554.18 |
| Curing | 1554.40 | 1554.53 |
| Relaxation | 1554.52 | 1552.26 |

Figure 8 shows implemented encapsulation of FBG into PDMS. Dimensions of the sensor are 60x25x4 mm. The priority of the research was not achieving minimization regarding design.

**Fig. 8:** The spectral characteristic of FBG before and after curing.

Figure 9 shows Bragg wavelength dependence of encapsulated and non-encapsulated FBG on temperature.

Non-encapsulated Bragg grating at wavelength 1554.1203 achieves temperature sensitivity of 10.378 pm/°C. After encapsulation, the Bragg wavelength was changed to the value 1552.2551 nm and temperature sensitivity was increased to 39.44 pm/°C. Our results correspond to the results of the paper [4].

## 4. Conclusion

The aims of authors were both an analysis of the impact of high temperature and itself curing of PDMS on spectral characteristics of FBG and temperature sensitivity of FBG within performed experiment. A secondary motivation is to use this encapsulation of FBG sensor in medical applications. The selected product was Sylgard 184 due to suitable properties. PDMS has very good heat resistance, excellent elastic properties, harmlessness, non-toxicity, non-flammability, and electric non-conductivity. Realization of encapsulation of FBG was split into consecutive phases. At the beginning, we made a reference measurement of spectral characteristics of FBG. The obtained data were compared with the encapsulated FBG, including a 50-min relaxation period, until the stabilization of Bragg wavelength (Tab. 1 and Fig. 7). At all stages of the encapsulation, we monitored the influence of temperature, the curing, and the mechanical stress on spectral characteristics of FBG and temperature sensitivity of FBG (Fig. 6 and Fig. 9). The presented results indicate that this type of encapsulation does not affect the structure of the FBG, it does not affect the functionality, and it represents an alternative method of encapsulation of FBG. The advantage is the fact that we can use the potential properties of PDMS, and we can expand potential application utilization of FBG in the sensor applications including medical ones.

A follow-up research will focus on both the analysis of the influence of different temperatures and duration of curing on the spectral characteristic of the FBG, the reflectivity of FBG, temperature sensitivity, and deformation sensitivity. The reproducibility experiment is also a future goal. This research was not the subject of this article.

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