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Optical pressure sensors in LTCC technology

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Abstract:
This paper deals with the design, manufacturing and measurement of optical pressure sensors developed in Low Temperature Co-fired Ceramic technology. Two types of the optical measurement methods were used for the pressure sensing. The first method is based on the distance measurement using Fabry Perot resonator. The second type of pressure transducer is based on the change of the light spectrum reflected from the Fiber Bragg Grating integrated in the sensor. LTCC ceramic structure with membrane was used for the forming of a pressure transducer. Both of the sensor types were designed to measure pressure in range of ± 0,5 bar difference atmospheric pressure.

INTRODUCTION

Pressure sensors are one of the most common sensor types available on the market. Optical pressure sensors compared to the other types of pressure sensors have many advantages, but are considerably more expensive in the means of interrogation. Therefore the use of this type of sensors is limited to the field of special applications. In the applications such as pressure sensing in hazardous environment, it is more important that sensors have excellent chemical stability of the material than the price of the final sensing system.
There are many types of ceramic pressure sensors based on different principles of sensing [1][2].
Optical sensors have many advantages compared to the other types of sensors. They are immune to the electromagnetic disruption, they can work over great distances from the interrogation unit and can be used in harsh and explosive environment.
Low Temperature Co-fired Ceramics (LTCC) is mainly used for electronic modules and packages. Lately this technology starts to be used in the field of sensing applications. Structures based on LTCC can be used as a mechanical transducer or as a substrate for different types of sensing layer. Pressure sensors based on LTCC are widely used, employing a variety of sensing methods based on the mechanical transducers like membranes. The most common method of pressure sensing is using piezoresistive elements with resistors in bridge configuration [3][4]. Other frequently used methods are based on the piezoelectric, capacitive or inductive structures. Rarely, we can meet special methods of pressure sensing like sensors based on field emission principle [5].
Most pressure sensors use membranes, which deflects under applied pressure. The material of the membrane can vary depending on the demands of the environment and reliability. Properties of the membrane in terms of deformation under the pressure are defined by the physical dimensions of the membrane and by the material properties.

MEASUREMENT METHODS

The most common principle of pressure sensing is using deformation elements such as membrane, which deflects under applied pressure. The deflection is converted to the change of electrical or other quantity easy to measure. Two methods of converting mechanical deflection of the membrane to the optical quantities are used in this paper. First method uses a Fabry-Perot (FP) resonator for pressure conversion to the length of the optical cavity, in our case the distance between the tip of the optical fiber and the membrane is measured. The second used method employs FBGs and conversion of deflecting membrane to the strain in the FBG structure. Strain applied to the FBG by the membrane under the pressure is measured. Both measurement methods need a spectral evaluation of the light signal.

Measurement using FP resonator

Optical resonators are usually used as a filter for signal interrogation, laser resonators or are employed in wavelength division multiplexing. In some sensor application, there is a possibility to use the FP resonator cavity as a sensing element. Generally FP resonators are very sensitive to the change in the resonator length caused by the temperature or by some other influence. In the measurement setup there is FP resonator used in reflective mode with only one signal port used for input and output of the light signal.
Measurement setup with outlined spectral characteristics of the light signals is shown in the figure 1.

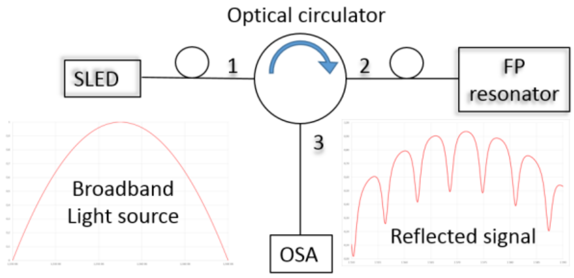

Fig. 1: Measurement setup for evaluation of the length of FP resonator

Modulation of the light signal intensity is caused by interference of incident light from mirrors at each end of the resonator. Distance between these two mirrors defines the length of the FP resonator. Positions of the light intensity minimums depend on the mirror spacing and are defined by equation 1. For any given length of the resonator there are resonant wavelengths according to the interference between two counter propagating light waves in the resonator. On the broadband spectrum, there is a visible power modulation according to this interference. The position of these peaks and valleys are determined by the equation:

$$L = \frac{\lambda_1 \lambda_2}{2(\lambda_1 - \lambda_2)} \qquad (1)$$

Where L is the length of the resonator and λ1, λ2 are the positions of resonant wavelengths in the spectrum.

Measurement using FBGs

The second measurement method is based on the shift of the central wavelength reflected from the Fiber Bragg Grating. FBGs are widely used in telecommunications as a band-pass filters in signal multiplexing. Measurement setup for the FBGs is also based on the evaluation of the reflected signal from the sensing element. The schematic of the setup for pressure measurement with FBG is shown in figure 2.

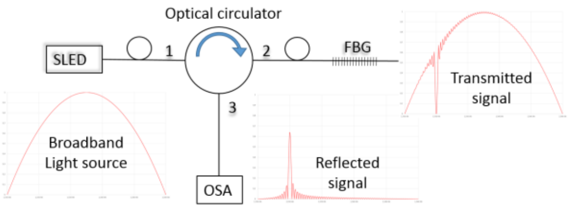

Fig. 2: Measurement setup for interrogation of the FBG pressure sensor

The structure of the FBG is created by alternating changes in refractive index of the fiber core (defined as the grating period - Λ). Reflected and transmitted light changes with a physical change of the optical fiber with grating. This effect is described by the equation:

$$\lambda_B = 2 n_e \Lambda \qquad (2)$$

Where λB is the wavelength reflected by the grating, ne is the effective refractive index of the optical fiber core.

SENSOR DESIGN

The sensors described in this paper were designed as the absolute pressure sensors for measurement of the pressure in the range of ±0,5 bar around the atmospheric pressure.

Both designed sensors have basically the same principle of pressure to displacement conversion. The main part of each sensor is a membrane, which deforms under the applied pressure. The main limitation in the sensor design is the thickness of the membrane. Minimal thickness of the membrane after firing process is given by the thickness of a single green sheet. In our case the minimal thickness (*t*) of the membrane is around 100 µm. There are also other parameters influencing the mechanical behavior of the membrane: material constants (Young's modulus - E, Poisson's ratio - γ) and dimensions of the membrane (radius - a, thickness - t). Deflection of the membrane under applied pressure can be calculated using the following equation:

$$d = \frac{3\, P_0\, r^4 (1 - \nu^2)}{16\, E\, t^3} \qquad (3)$$

Circular membranes have been designed to be one layer thick (approximately 100 um after firing process) and 7 mm in diameter. Membranes with these dimensions are the most sensitive to the pressure changes in the range of 0,5 bar around the atmospheric pressure.

Design of the FP based optical sensor

In this sensor, there are two mirrors, one of them is half mirror at the end of the optical fiber and the other one is highly reflective mirror at the surface of the membrane. Reflective layer on the membrane has to be highly reflective for the reduction of the signal loss. Reflectance of the bare optical fiber end calculated using Fresnel equations is usually around 3 %, depending on the used optical fiber. This reflectivity is sufficient for reliable signal detection in a specific configuration of resonator length and reflective layer quality. Cross-section of the FP resonator based sensor is shown in figure 3. Quality of the signal obtained from the FP resonator depends on the distance between mirrors and losses of the light signal in the optical cavity. All sensors are designed to have the cavity length of 200 µm and they give signal modulation of 15 dB.

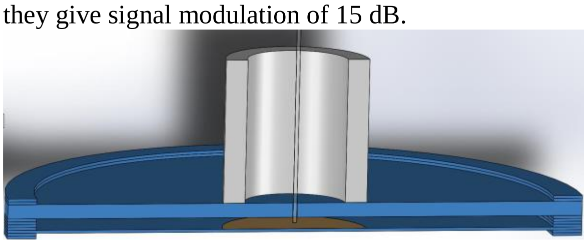

Fig. 3: Cross-section of the ceramic sensor based on the FP optical resonator

Design of the FBG optical sensor

Sensors based on the FBGs are working on the same transducer principle as the FP based sensors. Construction of the FBG sensor is almost identical as in the figure 3. The difference between these two types is in the fiber position. In case of FBG sensors the fiber is attached to the membrane using adhesive. During the manufacturing process FBG is fixed to the membrane with pre-applied strain. In case of our sensor design, the compressive stress from the pressure load is applied to the FBG, therefore, reflected central wavelength of the FBG will shift to the lower wavelengths with rising pressure.

SENSOR MANUFACTURING

Both types of sensor are created using LTCC technology. LTCC material in the fired state exhibits good mechanical properties, air tightness and good chemical resistance.
The standard manufacturing process of sensors consists of several steps. First, single layers of green sheets are laser cut according to the design. Next, green tapes are blanked and preconditioned. In the next step, raw ceramic is laminated and fired. In case of the FBG sensors there was whole sensor body laminated using progressive lamination and fired. The more complicated manufacturing process had to be used in case of FP based sensors. First, the sensor body and the membrane were manufactured using LTCC processes described above. Then the gold metal-organic layer is deposited on the membrane after the first firing process, this additional reflective layer is fired in a belt furnace using standard one hour firing cycle for thick film processing. Both parts of the sensor are bonded using green LTCC tapes and fired under applied load.
Optical fiber for the measurement is glued to the sensor body using epoxy adhesive. Glass or ceramic tube is bonded to the LTCC body for the mechanical robustness.

SENSOR MEASUREMENT

Light source used for the measurement is broadband SLED operating at the communication wavelength 1550 nm with bandwidth of 40 nm. For the interrogation of the spectral response we used Optical Spectral Analyzer (OSA) connected with the computer.
For the calibration of the sensor we used a pressure chamber up to 10 bar. This chamber has the capability of sealed operation. Measurement of the sensors was performed in both directions – in rising pressure and declining. Pressure in the chamber was set using computer controlled electromagnetic valve. Each sensor was measured in multiple cycles of rising and decreasing pressure.

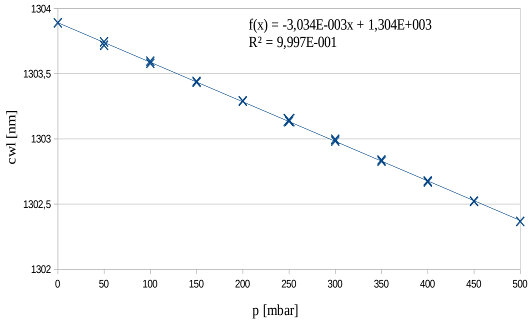

Fig. 4: Calibration characteristics of the FBG based pressure sensor.

Measured calibration characteristic for the FBG type sensor are shown in figure 3. Sensors based on the FBG exhibits god linearity. The sensitivity of 3 pm/mbar was achieved.

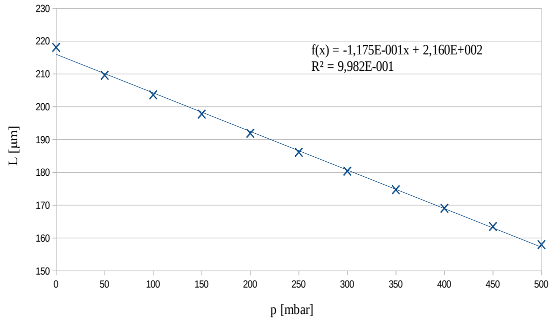

Fig. 5: Calibration characteristic of the FP based pressure sensor.

Measurement results of the FP based pressure sensor are shown in the figure 5. We got the sensitivity of 120 pm/mbar in change of the resonator length depending on the applied pressure.
Both types of sensors exhibit pretty good linearity over the designed operation range. For FBG sensor this is achieved by the prestrain of the FBG and the designed small range of the motion of the membrane in the sensor.
Sensors based on the FP resonator exhibit better sensitivity than the FBG ones with the use of the same interrogation unit, but they are more difficult to analyze. On the other hand, the design with the FBG presents membrane bonded to the optical fiber. This configuration increases stiffness of the membrane and improves resistance to the vibrations.
The interrogation unit with the spectral resolution of 1 pm was used for the calibration of the pressure sensors. This gives that the theoretical sensitivity of the sensors with the same membranes and the same interrogation unit is 0,3 % for the FBG based sensors and 0,1 % for the FP based sensors.

CONCLUSION

In this paper, we demonstrated two designs of optical pressure sensors based on the LTCC ceramics.

Experiments showed the possibility of manufacturing the optical pressure sensors in LTCC technology in combination with fiber optics. This combination brings unique properties of the sensors in terms of use in the hazardous environments and high sensitivity. Sensitivity of the FBG pressure sensors is around 3 nm/bar and accuracy ±0,3 %. Sensitivity of the FP pressure sensors is around 120 μm/bar and accuracy ±0,1 %. Sensors based on the FP resonator exhibit higher accuracy, but sensors based on the FBGs are more resistant to the environmental influences such as vibrations and are easier to interrogate.

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