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A highly sensitive fiber Bragg grating diaphragm pressure transducer

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ABSTRACT

In this work, a novel diaphragm based pressure transducer with high sensitivity is described, including the physical design structure, in-depth analysis of optical response to changes in pressure, and a discussion of practical implementation and limitations. A flat circular rubber membrane bonded to a cylinder forms the body of the transducer. A fiber Bragg grating bonded to the center of the diaphragm structure enables the fractional change in pressure to be determined by analyzing the change in Bragg wavelength of the reflected spectra. Extensive evaluation of the physical properties and optical characteristics of the transducer has been performed through experimentation, and modeling using small deformation theory. The results show the transducer has a sensitivity of 0.116 nm/kPa, across a range of 15 kPa. Ultra-low cost interrogation of the optical signal was achieved through the use of an optically mismatched Bragg grating acting as an edge filter to convert the spectral change into an intensity change. A numerical model of the intensity based interrogation was implemented in order to validate the experimental results. Utilizing this interrogation technique and housing both the sensing and reference Bragg gratings within the main body of the transducer means it is effectively temperature insensitive and easily connected to electronic systems.

1. Introduction

It is well understood that electronic sensors have limited capabilities in certain conditions such as harsh environments where there is risk of sparks causing an explosion, in extreme temperatures and pressures [1], or high electromagnetic interference (EMI), such as overhead transmission lines [2]. These are the areas where optical fiber sensors offer an attractive alternative due to their small size and weight, immunity to EMI, and needing no power supply [3]. Similarly, optical fiber sensors could replace electronic sensors in more mainstream applications because of other desirable attributes: low cost, high sensitivity, and passive nature [4]. Provided the sensors have similar physical properties to electronic sensors such that they can be easily installed and removed, are as rugged as their electronic counterparts, and the complexity and cost of optical fiber sensing systems is comparable to equivalent electrical systems, optical fiber systems could potentially replace many electrical systems in the future.

Fiber Bragg grating (FBG) sensors exhibit all of the benefits associated with optical fiber sensors, not least their ability to be multiplexed [5]. Many different FBG sensors have been developed with almost all measurands being manipulated to cause either a change in the effective refractive index or in the grating period of the FBG. These measurands include temperature, strain, level, flow, and pressure [6]. Most of these variables can be measured using a bare fiber FBG, although the sensitivity and dynamic range of these sensors would be essentially fixed without the development of appropriate transducers. By designing proper mechanical systems in conjunction with FBG sensing technology, highly sensitive instruments with the desired attributes for any given application can be obtained. Furthermore, by manipulating the optical response of the FBG it is possible to use simpler interrogation techniques rather than being forced to use expensive solid state optical interrogators.

Appropriate pressure transducers are desirable as the intrinsic sensitivity of bare FBGs is only 3.04 pm/MPa [7], which is far too low for most pressure sensing applications. Hence, virtually all FBG pressure sensors actually measure the strain induced wavelength shift and relate it to a change in pressure. Liu et al. reported simultaneous measurement of pressure and temperature using a polymer coated FBG. Their results showed a sensitivity of −80 pm/MPa and 88 pm/°C at 1540.2 nm [8]. They then increased

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the sensitivity of their sensor to −5.28 nm/MPa by embedding the polymer coated FBG in an aluminum cylinder [9]. In their later work, with the polymer coated FBG embedded in a copper cylinder, they report a sensitivity of −3.77 nm/MPa at 1558 nm but with improved thermal stability [10]. The group then reported an ultra thin FBG pressure sensor with the FBG bonded perpendicular to a diaphragm causing the FBG to stretch along the length of the FBG under pressure. They studied the effects of varying the radius and Young's modulus of the diaphragm. When optimized, the sensitivity is as high as 7 nm/MPa.

Optical fiber pressure sensors based on traditional pressure transducers have also been reported. Huang et al. described a Bourdon tube with an FBG attached to it which had a sensitivity of 1.414 pm/kPa across a range from 0 to 1 MPa [11]. The same group also reported a diaphragm type FBG pressure sensor with a sensitivity of 1.57 pm/kPa across a range from 0 to 1 MPa. By using two FBGs and analyzing the difference in the wavelength shift, the temperature sensitivity was effectively eliminated [12]. Similarly, other groups such as Vengal Rao et al. [13] and Xiong et al. [14] have also described diaphragm type FBG pressure sensors where the FBG is bonded perpendicular to the diaphragm surface with a U-shaped clamp. They report a sensitivity of 31.67 nm/MPa and 3.55 nm/MPa, respectively. Pressure sensors using long period gratings [15] and microstructured optical fibers [16] have also been demonstrated.

Here, a highly sensitive diaphragm based pressure transducer for extremely low pressure applications has been developed. The response of the transducer has been modeled using small deformation theory and the results have been compared to analogous experiments. Furthermore, a simple ultra-low cost interrogation technique has been implemented in an attempt to increase the penetration of FBG sensors into mainstream industrial processes by making them easily compatible with current electronic controllers. By splitting the reflected signal into two, and using one signal as a reference, or by comparing the transmitted and reflected signals, it is possible to overcome issues associated with intensity based interrogation techniques, such as optical power fluctuations [17]. Moreover, the simplicity and reduced cost of the interrogation far outweigh the disadvantages, particularly in quasi-static applications.

2. Transducer design and modelling

Diaphragm pressure transducers incorporating FBGs bonded to a metallic diaphragm have been designed, tested and reported [13,18,14,12]. Typically, the Young's modulus and physical dimensions of the diaphragm are much greater than that of the fiber, and in turn, of the grating. Hence, the stress induced wavelength shift is essentially determined by the physical properties of the diaphragm. When considering the use of a rubber diaphragm this is no longer the case. The Young's modulus of the silica fiber is significantly greater than that of the diaphragm, such that the fiber itself is the limiting factor determining the strain induced wavelength shift, particularly in the region of the bonded FBG. However, it is shown that the sensitivity of the transducer is strongly correlated to the radius of the actual diaphragm. Modeling based on small deformation supports this hypothesis and agrees with experimental data.

2.1. Transducer design

A common rubber material was used as the elastic body for the diaphragm pressure transducer. A small circular piece of the rubber, with a radius of approximately 14 mm, was bonded to a plastic cylinder, while the FBG was bonded near the center of the rubber diaphragm. The Young's modulus of the rubber used was experimentally determined using a PASCO stress/strain apparatus and found to be approximately 1.4 MPa. Likewise, the Young's modulus of the silica fiber was measured to be approximately 50GPa. Because of the relative sizes and moduli of the fiber and diaphragm, the fiber was estimated to provide a factor of 200 greater resistance than the diaphragm, and consequently the set up can be considered to be completely controlled by the fiber.

2.2. Small deformation

The elastic body of the transducer is a circular flat diaphragm. As pressure is applied to one side of the diaphragm, strain is imposed on the diaphragm, distributed about its center. Provided the edge of the diaphragm is fixed to a cylinder, and the applied pressure is uniform across the entire diaphragm, the strain at any point on the diaphragm can be calculated using small deformation theory [19]. Small deformation theory specifically describes the radial, ϵ_r, and the tangential, ϵ_t, strain at any point on a circular diaphragm as a function of applied pressure, P, given by [20]:

$$\epsilon_r = \frac{3(1-\nu^2)\left(R^2-3r^2\right)}{8Eh^2}P \tag{1}$$

$$\epsilon_t = \frac{3(1-\nu^2)\left(R^2-r^2\right)}{8Eh^2}P \tag{2}$$

where E is the Young's modulus of the material, h and R are the thickness and radius of the diaphragm, respectively, and r is the distance from the center of the diaphragm to a point of measurement. At the center of the diaphragm the magnitude of the total strain, ϵ_c, is given by:

$$\epsilon_c = \frac{3\sqrt{2}(1-\nu^2)R^2}{8Eh^2}P \tag{3}$$

Fig. 1 shows the normalized strain distribution curves for a circular diaphragm. The stain distribution curves for the proposed design were also modeled using small deformation theory, as shown in Fig. 2. The parameters used were: Young's Modulus $E = 50$ GPa, Poisson's ratio $\nu = 0.19$ [21], radius $R = 14.0$ mm, and the thickness $h = 0.125$ mm.

3. Theoretical and experimental strain induced Bragg wavelength shift due to pressure

FBGs are used extensively in the telecommunications industry as add drop multiplexors, although they are becoming more and more favorable as distributed sensing elements. The Bragg wavelength shift of an FBG has been documented for over 30 years [22,23], and is essentially due to a temperature variation or an external applied strain, although they have been shown to measure an array of different environmental conditions.

3.1. Fiber Bragg grating fundamentals

A fiber Bragg grating is an optical filter written into the core of an optical fiber using a high energy optical source and a phase mask [24]. An in-line optical grating with regions of alternating refractive index is produced. The grating, when illuminated by a broadband light source, causes many partial reflections to occur within the different regions such that a specific narrow band is reflected from the grating and all other wavelengths are transmitted. The peak reflected wavelength is known as the Bragg wavelength, λ_B, and is determined by the effective refractive index, n_{eff}, of the grating and the grating period Λ, as: