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A highly sensitive multiplexed FBG pressure transducer based on natural rubber diaphragm and ultrathin aluminium sheet

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ABSTRACT

Pressure measurement with a good sensitivity has always been a concern in most of the engineering applications and biomedical field. In this paper, a multiplexed FBG bonded on an ultrathin aluminium sheet which act as a cantilever deflected due to a deformation from a natural rubber based diaphragm has been proposed and studied. By using two gratings inscribed on a single optical fibre which senses the positive and negative strain has enhanced the sensitivity of the pressure transducer recorded at 329.56 pm/kPa or corresponding to 10.7893 kPa^{-1} across the range of 0 to 10 kPa with a good linearity of 99.76%. Furthermore, the thermal cross-sensitivity is compensated.

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1. Introduction

Pressure transducer with a high sensitivity has become a necessity criterion in most of the industrial process and especially in biomedical applications [1,2]. As discussed in most of the work [3–6], FBG pressure sensor has more superiority as compared to electrical pressure sensor such as strain gauge in terms of immunity to electromagnetic interference (EMI) and unsusceptible to spark making them suitable for harsh environmental monitoring free from causing of explosion. Moreover, multiplexing capability of the FBG sensor making them favourable for multipoint measurement. More than 20 years ago, Xu et al. [7] have developed an applicable bare FBG pressure transducer with a sensitivity recorded at 3.04×10^{-3} pm/kPa. However, the sensitivity is extremely low to be utilised for pressure sensing.

Over the years, various packaging method and modification on the FBG sensor has been optimized to enhance the sensitivity of the pressure transducer [8–21]. Fabry-Perot (FP) interferometric sensors have reported on an extremely high sensitivity [22–25]. However, FP sensors are relatively expensive and complicated in configuration making the straight forward pressure transducer restricted for market penetration. Several special optical sensors have also been investigated. Tapering of long period grating (LPG) sensor has recorded a sensitivity at 0.051 pm/kPa [26]. However, LPG sensor has high thermal cross-sensitivity which can influence the pressure performance [27]. Chemically etching away the polymer FBG obtained a sensitivity at 1.2 pm/kPa [1]. However, reducing the diameter of an optical fiber making the sensor more fragile to environmental perturbation [27] which limit its harsh environmental utilisation. Micro fabrication technique by combining optical fibres with Micro Optical Electro Mechanical System (MOEMS) retrieved a sensitivity at 6 pm/kPa [28]. Air hole microstructured photonic crystal fibre obtained a sensitivity at 0.04415 pm/kPa [29]. Microstructured optical fibre recorded a sensitivity at 0.033 pm/kPa [30]. However, such sensor are complicated and not easy to be fabricated. Furthermore, multiple sensors in a single optical fibre are difficult to be multiplexed for multiple sensing and as temperature compensation.

Huang et al. [31] have utilised two standard FBGs bonded on a circular diaphragm which consequence in red shift and blue shift of the reflected spectrum. Subtracting away both the contrasted shifts, obtained a temperature compensated pressure sensitivity at 1.57 pm/kPa. According to the authors, such method will also enhanced the sensitivity as compared to utilisation of only single FBG [31]. The same method have also been reported in [32] and [33] with sensitivity obtained at 1.8×10^{-2} MPa^{-1} and 1.414 pm/kPa, respectively. Recently, Liang et al. [34] have utilised two FBGs bonded on top and bottom of the cantilever beam. The cantilever was connected by a dowel bar to a flat diaphragm. During pressurisation, the diaphragm will deform and deflect the cantilever. However, the temperature insensitive pressure sensitivity was recorded at only 0.34 pm/kPa [34]. This is due to the high Young's modulus of the diaphragm which restricted its

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deformation to be transferred to the cantilever beam. In addition, such method can also be simplified by multiplexing a single optical fibre with two gratings instead of using two FBGs.

Thus, in this paper, we have inscribed two gratings on a single optical fibre and bonded the sensor to the top and bottom surface of a thin aluminium sheet which act as a cantilever. The aluminium sheet will deflect due to a transferred concentrated point force from a circular plastic rod firmly fixed to the centre of a low Young's modulus natural rubber diaphragm. The proposed method have enhanced the sensitivity of the pressure transducer recorded at 329.56 pm/kPa across 10 kPa with a good linearity of 99.76%. Furthermore, the thermal cross-sensitivity is compensated.

2. Sensing principle of the FBG pressure transducer

The schematic design of the proposed FBG pressure transducer is shown in Fig. 1. As a proof of concept, the transducer consists of two parts printed by using 3D prototyping machine namely pressure chamber and retaining ring. A common natural rubber circular diaphragm is sandwiched between the pressure chamber and retaining ring. A total of eight M4 × 30 mm Allen bolts was used to firmly tighten the retaining ring to the pressure chamber.

A circular plastic rod is securely glued to the centre of the rubber diaphragm and attached to the thin aluminium sheet. Here, an aluminium sheet is used instead of other metallic materials due to the non-corrosive properties [35] making the pressure transducer suitable for underwater utilisation. The aluminium sheet is bolted to the retaining ring and the edge is positioned exactly on top of the plastic rod. During pressurisation, the rubber diaphragm deformed and the plastic rod pushes the aluminium sheet cantilever beam upwards as shown in Fig. 1(c), and back to original position during depressurization. A bare single optical fibre multiplexed with two gratings at 10 cm apart and grating length of 1 cm was bonded at the centre of the aluminium sheet. One grating was located on top of the aluminium sheet while the second grating was positioned at the bottom. A Cyanoacrylate adhesive glue with density of 1.10 g/cm^3 and Barcol hardness value of 65 is used for all the bonding operation. The FBG bonding process is performed by gluing along the length of the grating and firmly pressed with a smooth Teflon film for 10 seconds to improve the bonding strength and minimize the non-uniformity as possible. The length of the grating has no significant influence on the sensitivity. However, the hardness strength of the adhesive highly influence the true strain on the FBG where a loose bonding might result in low sensitivity due to non-uniform strain. The pressure chamber was fixed with a 12 mm × 40 mm male air hose fitting which gives a universal snap-fit applications to any 12 mm female pneumatic coupler.

As the pressure chamber is pressurised, the rubber diaphragm will deform and pushes the plastic rod exerting a concentrated point force on the cantilever aluminium sheet. The cantilever sheet will deflect and results in Bragg wavelength shift of both the FBG sensors. Since FBG 1 was bonded at the bottom surface resulting in wavelength shift due to positive strain which can be expressed as [21,34]:

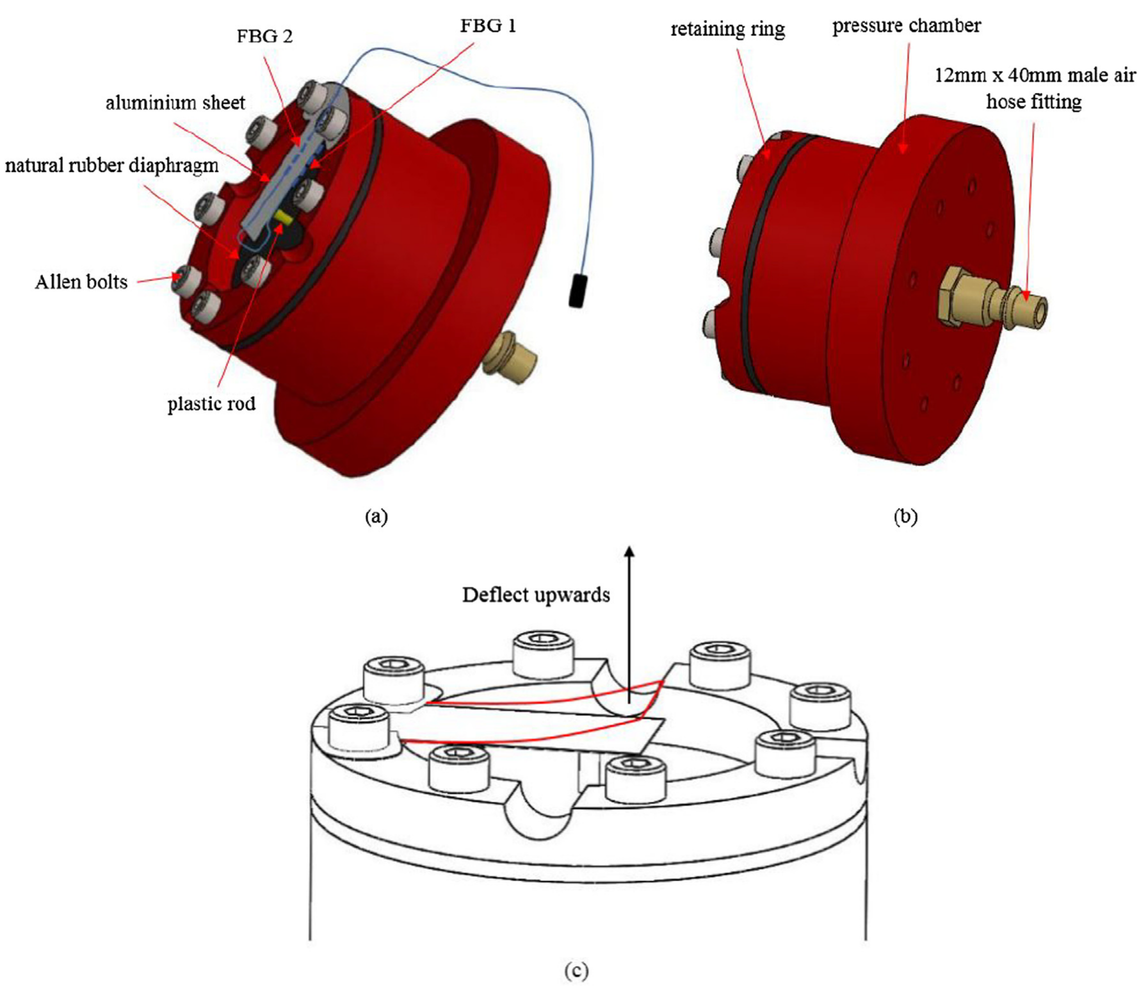

Fig. 1. The schematic design of the pressure transducer: (a) Side view (b) Back view (c) Deflection of the cantilever beam during pressurisation.

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