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The Use of Bragg Gratings in the Core and Cladding of Optical Fibres for Accurate Strain Sensing

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Abstract: Optical Fibre Sensors (OFS) have many advantages over others type of sensors for measuring strain or micro-displacement. This paper introduces a new configuration of Bragg gratings within an optical fibre to improve strain measurement resolution and accuracy. We describe the geometry, together with the research direction currently being undertaken to produce a commercially viable micro-displacement sensor suitable for a number of architectural and engineering application. *Copyright © 2008 IFSA.*

Keywords: Optical fibre, Strain, Bragg, Micro-displacement

1. Introduction

The ability to perform distributed strain measurements over a structural beam is of considerable importance in assessing both the safety and maintenance requirements of most civil engineering structures. There is an increasing awareness that efficient Structural Health Monitoring (SHM) can substantially decrease the maintenance expenditures of many structures and alleviate delays caused by unnecessary or unexpected repairs. As an example of this, the structural health monitoring of bridges has become a significant issue over the last decade. In the United States alone there are some 591,707 major bridges, nearly a third of which are classified as deficient or functionally obsolete [1]. The annual budget for maintenance is around US\$4 billion, though it is estimated that approximately US\$13.5 billion annually is required to repair and maintain all bridges to an acceptable level. This huge expenditure has placed considerable pressure on administrative bodies to put into place advanced bridge management programs, including real time structural monitoring and assessment instrumentation [2].

The importance of SHM has attracted the attention of those working in the emerging field of Optical Fibre Sensors (OFS) and many advances have been made in techniques to enable such measurements (e.g. [3]). Much of this interest has been prompted by the relative inertness of optical fibres to environmental factors (e.g. moisture) and their low interference to the beam's structural integrity (i.e. small cross section) making them ideal candidates for the desired distributed measurement process.

Strain and loading measurements most often use devices firmly fixed to the sample to measure its micro-displacements under the action of some force. Bragg gratings etched within optical fibres do this by indicating the change in grating spacing as the fibre is stretched along with the sample (e.g. [4]). The practical application of such technology however has a number of drawbacks, including; 1) the response due to increased grating spacing is similar to that imposed by changes in temperature so the two effects are difficult to resolve, 2) fixing the fibre within or on the sample so that the fibre actually measures its true displacement is also difficult (while maintaining its major advantage of having a small cross section), 3) the strain induced deformation of along the fibre is not uniform and this effect is difficult to allow for [5]. It is the purpose of this paper to outline work currently under way to develop a robust and commercially viable Bragg grating strain sensor that can be used in a variety of measurement scenarios, while mitigating some of the major disadvantages.

2. Bragg Sensors

Bragg grating technology is one of the most popular choices for OFS strain measurement sensors due to their simple manufacture (direct etching in the fibre core) and relatively strong reflected signal strength. Other OFS types, such as Fabry-Perot interferometers, are less popular since signal detection and resolution can be problematic requiring expensive equipment and specialist operators.

Fig. 1 shows the typical arrangement used in current strain (micro-displacement) sensors. When a force is applied to the ends of the fibre sensor, the Bragg line spacing is increased and this results in a frequency shift of the backscattered peak.

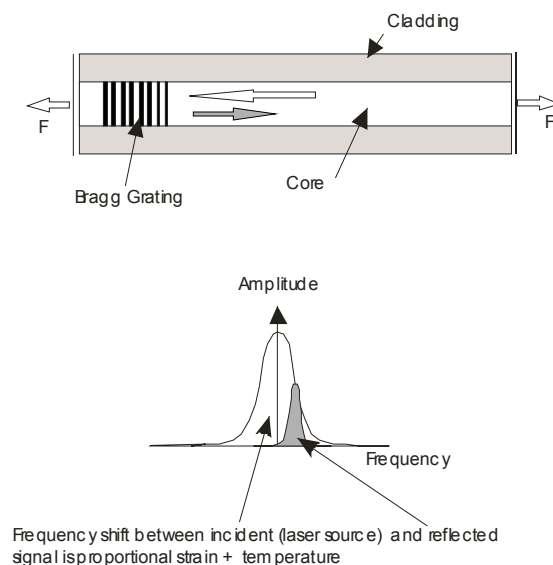


Fig. 1. Basic concept behind a Bragg grating strain sensor.

The frequency of the Bragg scattered component within an optical pulse is given by:

$$\lambda_B = 2n\lambda_G, \quad (1)$$

where λ_B is the scattered Bragg wavelength, λ_G is the grating wavelength and n is the refractive index of the fibre core. The change in the Bragg wavelength ($\delta\lambda_B$) is given by [6]:

$$\delta\lambda_B = 2n\lambda_G \left[\left(1 - \frac{n^2}{2} (P_{12} - \nu(P_{11} + P_{12})) \right) \delta\varepsilon + \left(\alpha + \frac{1}{n} \frac{dn}{dT} \right) \delta T \right], \quad (2)$$

where:

P_{11} and P_{12} are components of the fibre strain tensor;

$\delta\varepsilon$ is the applied longitudinal strain;

ν is Poisson's ratio;

α is the coefficient of thermal expansion and

T is the temperature.

So a spectral shift is also generated by changes in the fibre temperature with the overall shift being a combination of the two effects.

The coefficient of thermal expansion, α is very small and for silica fibre:

$$\frac{n^2}{2} (P_{12} - \nu(P_{11} + P_{12})) \approx 0.22$$

so that equation (2) becomes:

$$\delta\lambda_B = 2n\lambda_G \left[0.78 \delta\varepsilon + \frac{1}{n} \frac{dn}{dT} \delta T \right] \quad (3)$$

In practice it is difficult to resolve the $\delta\varepsilon$ and δT component contributions of the spectral peak shift, $\delta\lambda_B$. Attempts have been made to combine two fibres, one under strain while a neighbouring one is shielded from the strain, in an effort to calibrate the temperature response. This approach works to some degree, but that fact that two fibres have to be excited in exactly the same manner for the small differences to be measured, means that a considerable degree of accuracy in relative fibre placement and detector sophistication is required. Other methods using several wavelength gratings and/or fibre dispersion properties have met with even less success, again because of the small differences involved.

As well as temperature effects, other practical considerations need to be addressed when constructing a Bragg grating OFS. Table 1 lists some of these. Here interrogation techniques (including multiplexing) are not included, with the focus being upon the accuracy and reliability of the sensor itself.

Table 1. Some of the major problems facing the use of Bragg gratings in strain measurement sensors.

Sensitive to a Temperature	The Bragg grating response will also be dependent on temperature. It is difficult to unwrap this from strain and this is the major inaccuracy involved.
Localized effects	Localized "pinching" around the grating will cause it to be distorted and thus give a false indication of the distributed strain (i.e. strain over some longer length)
Bonding to the substratum	To measure strain the fibre jacket needs to be firmly bonded to the material. In external placements particularly, the small amount of movement to be measured may reside in fixings and glue etc. and not the fibre.
Small dynamic range	The range of measurable strain is quite small (from zero to about 1000 μ strain – 2000 μ strain) so peak detection and thus resolution are critical.

3. Dual Bragg Gratings

When considering a reconfiguration of the Bragg grating system to achieve optimal measurement performance some important points are worth noting:

- Strain is given by $\Delta L/L$ where L is the original length and ΔL is the change in length due to stress. Thus to measure strain requires only the measurement of change in distance between allotted points.
- Bragg diffraction can be induced by inscribed lines in either the core or cladding of the fibre.
- The temperature sensitivity of the fibre is mostly (95%) due to the change in refractive index with temperature. A similar percentage change will occur within both the core and cladding material.

Since a proportion of the bound mode travels parallel to the core axis within the cladding material via evanescent propagation (and this can be increased by a variety of methods), a grating within this region may also act as a good scatterer. By mechanically detaching the cladding from the core so that each is free to move independently two sets of adjacent gratings may be constructed (Fig. 2).

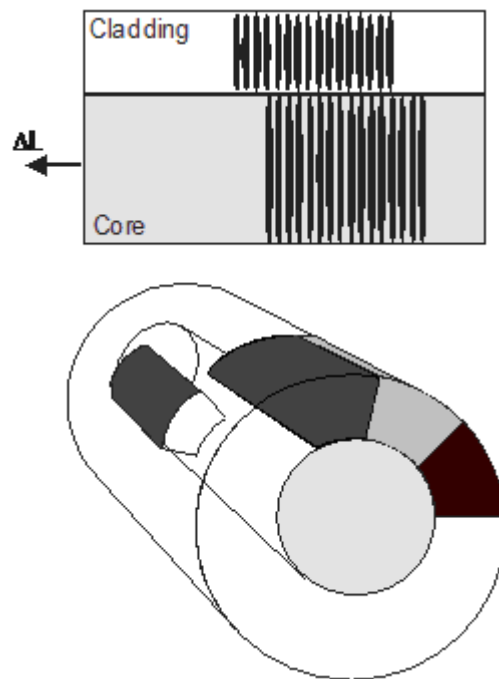


Fig. 2. Dual Bragg Gratings in core and cladding. The figure below shows a possible arrangement of cladding gratings to take advantage of a vernier geometry.

The optical properties between the two can be strictly maintained by applying liquid resins that are commonly used for other fibre optic matching purposes. Such a fibre, with Bragg gratings etched on both the core and cladding sections, will allow two new geometries to be exploited for micro measurement:

1. The cladding is under stress while the core is not. This means that both Bragg gratings will be under the same temperature and optical conditions, but with only one under stress. The current problems of providing a reference identical to the measurement sensor will be mitigated by this application.
2. Neither the core nor cladding is under stress, so that the Bragg gratings do not measure the micro shift by an increased grating spacing. Instead the relative displacement of the two is measured by a

adopting a Vernier scale. This method unwraps strain from temperature, but also has the added advantage that when fixing the sensor to the sample, no allowance has to be made for stress within the fittings; the sensor becomes a purely stress free measurer of micro-displacement. The change in grating spacing is thus solely due to temperature variation. This also overcomes the relatively limited strain range of the OFS.

These two approaches have a common starting point, the detachment of the core-cladding interface, and a significant part of future research will be devoted to this phase.

Of the two methods the detached Vernier geometry, while being the most difficult to realize, offers the greatest advantage for a strain sensor. Such a system can solve (or at least alleviate) most of the technical difficulties highlighted in Table 1. As a rough, but reasonable guide, equation (3) may be rearranged to give for constant strain:

$$\delta\lambda_B = 2n\lambda_G \left(\frac{1}{n} \frac{dn}{dT} \delta T \right), \quad (4)$$

giving:

$$\frac{1}{\lambda_B} \frac{\delta\lambda_B}{\delta T} = \frac{1}{n} \frac{dn}{dT} = 6.67 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}, \quad (5)$$

The numerical value assigned to equation (5) is given by [6] and [7]. If n is taken as the core refractive index and dn/dT is considered the same for the two media then it can be shown that the effect of temperature in grating separation between the core and cladding is around 10^{-14} °C, well below the expected system response of about 10^{-9} .

Since the strain is a measure only of the change in length there is no need for the fibre to be stretched in the manner of conventional techniques. This means that it is possible to shield the fibre from localized effects without effecting the strain measurement (see Fig. 3). The same argument leads to a reduction in the effect any bonding material may have in the measurement of actual strain as well as those problems caused by the non-homogeneous longitudinal strain field.

There are also some practical limitations on the type of optical fibre that can be used in the dual Bragg grating sensor as specified here and in [8]. If the sensor is indeed realized by the detachment of the core and cladding a simple step refractive index profile will need to be used. The normalized frequency, V , for a circular waveguide is given by:

$$V = \frac{2\pi\rho}{\lambda} (n^2 - n_{cl}^2)^{1/2}, \quad (6)$$

where:

ρ is the diameter of the core;

λ is the propagation wavelength;

n_{cl} is refractive index of the cladding.

For single mode operation it can be shown (e.g. [9]) that $V < 2.405$. The amount of power flowing in the core can be estimated by the Mode Field Diameter (MFD) and this is a function of V and the core radius ρ . For $V = 2$ the MFD can be used to show [6] that approximately 85% of power flows within the core (15% in the cladding) and this core value increases quickly as V becomes larger. The power propagating within the cladding must be sufficient for reflection discrimination and so requires $V < 2$.

This limits the fibre waveguide to single mode propagation, with a small normalized index difference, Δ , (see equation (8)) and small core radius (around 10 μm).

To provide the maximum number of combinations, the cladding gratings will need to be distributed in annular sections radially around the core. The number of possible sections will depend upon the resultant reflection amplitudes of constructive and destructive interference over the active region. This together with the minimum number of aligned etched lines and proportion of power that can be injected into cladding modes required for detectable scattering will need to be modelled carefully in the early stages. The modelling component should be a relatively straight forward process, but constructing the physical system will of course present many optical engineering constraints including all those usually associated with optical systems such as diffraction and etendue etc. as well as some unique to fibre propagation such as mode coupling.

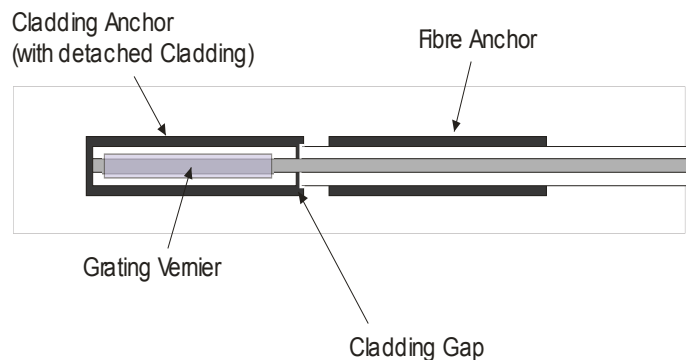


Fig. 3. Proposed housing for the Vernier geometry type sensor.

4. Current Research

Current work in constructing the two types of sensors described in the last section is focused upon mitigating against a number of operational problems, both observed and perceived.

The most obvious difficulty to be solved is the detachment of the core from the cladding in a way that allows independent movement without compromising the integrity of the waveguide performance. It is likely that lubricants of the correct refractive index exist that can be used for this purpose, though other solutions or mitigating procedures also need to be explored.

From equation (1) it can be seen that the refractive index of the medium will effect the Bragg spectral response. Typical step refractive index fibres have a normalized index difference (Δ) between 0.003 – 0.01. So using the lower limit:

$$\Delta = \frac{n_{co}^2 - n_{cl}^2}{2n_{co}^2}, \quad (8)$$

$$n_{cl} = 0.0997n_{co}, \quad (9)$$

Using equation (1) for constant λ_G and a 1300 nm laser source gives the change in the Bragg reflected wavelength between the core and cladding of:

$$\delta\lambda_B = \frac{\lambda_B}{n_{co}} \delta n_{co} \quad , \quad (10)$$
$$= 2.6 \times 10^{-9} m$$

where $\delta n_{co} = 0.003$. From equation (3) the Bragg wavelength shift due to a strain of 1000 μ strain (i.e. $\Delta L/L = 0.1\%$), at constant temperature is around $1 \times 10^{-9} m$. Clearly, even at the lowest values of Δ the impact of the different refractive indices is significant when considering the Vernier construction and this will need to be compensated for. One way of achieving this could be by creating different wavelength gratings λ_G , for the opposing Vernier components; though the required resolution may be difficult to achieve. Also challenging is the 3-Dimensional alignment of the gratings to provide adequate precision and coverage and will take some skill and undoubtedly increase the length of the fibre over which a single measurement can be taken.

For both geometries, mode coupling of the forward propagating paths is likely to be strong when a grating mismatch occurs (i.e. when the gratings are not aligned). This means that incorporation of more than one sensor per length of fibre may require different wavelength regimes, something already experimented with by others.

Since not all of the fibre cladding will be detached from the core there will be a region of discontinuity in the cladding. This is not in fact an unusual occurrence in commercial systems and there are a number of materials available to take the place of the cladding gaps. The trick of course will be to find one that does not alter the mechanical properties of the sensor (i.e. relative movement) while still guiding the required modes. This will in also require development of specialized housing to allow simple placement and efficient operation of the sensor (Fig. 3).

5. Concluding Remarks

The overall research objective is to produce an optical fibre sensor that unambiguously measures micro-displacement and which can be monitored using commercially available equipment. The system design will have in mind the further development of interpretive software and distributive sensing applications, some of which will require adaptation to specific applications.

This paper has described a new arrangement of Bragg Gratings within optical fibres that has the capability of satisfying these objectives. Since the work is in its initial stages we have outlined here the proposed geometry of the sensor together with the current direction of research to mitigate a number of practical design problems.

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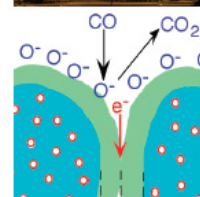
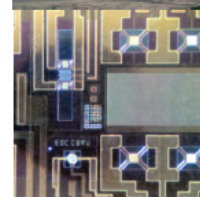
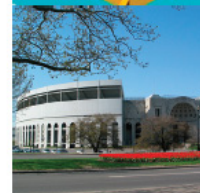
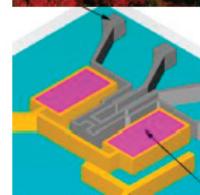
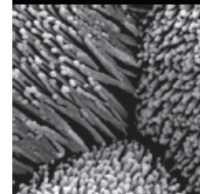
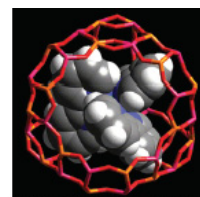
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