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7: CHARACTERIZATION OF TILTED FIBRE GRATINGS UNDER BENDING

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Abstract – The characteristics of low- and high-order cladding modes of tilted gratings (TFBG) under bending has little been investigated despite the popularity of TFBGs in different sensing applications. In this work a theoretical model to investigate the interaction between core and cladding modes in a bent fibre has been established. The influence of bending curvature on the low- and high- order cladding modes has been analyzed, based on the use of both simulation and theoretical calculation. The simulation and calculations carried out show that due to the different mode characteristics, the resonance wavelengths of the different cladding modes will shift in different way, as the bending curvature increases. A 3° tilted grating has been used as a bending sensor, whose operation was based on the mode characteristics of the low-order cladding modes. A linear response between the resonance wavelength of a low-order cladding mode and bending curvature has been obtained, creating a useful result for fibre optic bending mode sensors.

Keywords: Tilted Fibre Grating; Bending curvature; Cladding Modes Characteristics; Light Intensity Distribution; Resonance wavelength

1. INTRODUCTION

Fibre Bragg Gratings have attracted much attention since their initial development for a range of sensor applications. In addition to having both the advantages of optical fibre and optical fibre sensors, the features of wavelength modulation, ease of inscription and their multiplexing capability give them a key role in many measurement applications. Fibre Gratings, used as passive optical fibre devices are widely seen in different aspects of fibre optic sensing, optical communication, fibre laser and indeed other fields [1].

The Tilted Fibre Bragg Grating (TFBG) is a special type of short-period fibre grating in which a specific angle between the grating and the direction of the fibre axes is created, due to the non-perpendicular placement of the phase mask with regard to the grating axial direction, during grating fabrication. The tilt grating region thus formed causes the light propagating forward in the fibre core to be coupled backward into the core and cladding, so that both the core mode and a series of cladding modes in the tilted grating transmission pattern can be observed. The core and cladding modes in a tilted grating can be sensitive to changes in the external environment. By analysing the parity transmission response of the tilted grating, information on changes in external environmental factors such as temperature, refractive index, stress, curvature and so on can be deduced [2].

The research in the work described here on tilted grating characteristics has focused more on the measurement of important parameters such as refractive index, temperature and other useful characteristics [2], and they can have an important role in better Structural Health Monitoring (SHM) of buildings and other structures using them in fibre networks, as such tilted gratings are easy to embed in the structure. Their small size and large multiplexing capability allow them to be adapted to small, confined environments or large structures, as required. Further, sensing of fibre bending (and therefore the bending of structures to which the fibre is attached) remains one important applications of interest for TFBGs [3]. A number of investigations in which tilted grating based bending has been exploited are seen in the literature – where for example it has been suggested that the bent region of tilted grating has a significant impact on the transmission intensity of its low-order cladding modes [4]. An algorithm has been proposed for calculating the contour length of the low-order cladding modes to determine the degree of curvature [4] achieved. It has also been proposed to determine the magnitude of the curvature of the fibre (or the work piece to which it is attached) by determining the curvature cutoff mode of the lower order cladding modes [5].

So far the investigations on the bending characteristics of such tilted gratings have mainly focused on the influence of the bent grating on the transmission intensity of the low-order cladding modes, while the characteristics of the high-order cladding modes and the resonance wavelength shift of cladding modes under bending are little addressed. Given the importance of this in SHM applications, in this work, both a theoretical analysis and an experiment investigation have been carried out to understand better and thus to propose to exploit more widely the characteristics of low-order and high-order cladding modes of tilted gratings, under bending. To further verify the theoretical analysis a 3° tilted grating has been used here as a bending sensor. Results show that a linear relationship between the resonance wavelength of a low-order cladding mode and bending curvature has been obtained and results of the investigation of this are reported.

2. THEORY AND SIMULATION

2.1. Theoretical analysis

The electromagnetic field of the incident light modes in the fibre will interact in transmission, so that modal energy exchange occurs, the phenomenon of mode coupling. The refractive index of the ordinary single-mode optical fibre core and cladding are distributed showing a uniform circular symmetry, and as different modes are orthogonal to each

other, there is no energy exchange. The Tilted Fibre Bragg Grating (TFBG), due to its inclined periodic change of core refractive index, destroys the circular symmetry of the fibre and causes an energy exchange between different modes in the fibre. As a result, the forward-propagating incident light entering the grating region is coupled into the forward core mode, the backward core mode and the backward cladding mode.

When the TFBG is subjected to bending, the fibre axis is curved, leading to a varying effective tilt angle of the grating. It is suggested that the series of responses in the tilted grating transmission pattern caused by grating bending is due to the change in the effective tilt angle of the grating area [6]. Since the core/cladding diameter (9/125 μm) is small compared to the radius of curvature (10 mm – 10 m), the small change in the effective tilt angle caused by the bending of the grating area can be considered to have a small effect on the grating transmission pattern. In fact, when the grating area is bent, more light is coupled from core to cladding, which indicates the change in core/cladding effective refractive index. This consequently affects the grating transmission pattern [7].

As shown in Fig. 1, when a fibre is bent it will cause a longitudinal strain parallel to the optical axis. The strain can be expressed as:

$$\varepsilon = Kx \quad (1)$$

where K is the curvature of bending, which is the inverse of bending radius R . A change in the effective refractive index of the cladding/core then takes place due to the photo-elastic effect. The effective refractive index change, Δn , can be expressed as:

$$\Delta n = -(n^3/2)[(1 - \nu)p_{12} - \nu p_{11}]Kx \quad (2)$$

where ν is Poisson's ratio, p_{11} , p_{12} are the photo-elastic constants.

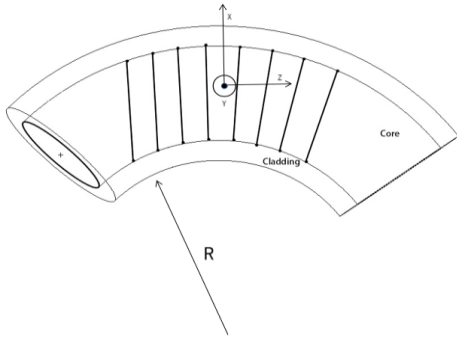


Figure. 1. Conceptual diagram of tilted grating area bending.

The above expression clearly shows the effect of bending on the effective refractive index of fibre grating mode. The optical field transmission inside the fibre, however, is affected by many factors, as discussed below.

Bending changes the symmetry of mode field distribution in the fibre, thus reducing the mode field overlap factor of the core guide mode and cladding mode. Further analysis shows that the change of the mode effective refractive index caused by the fibre bending is not only related to the bending curvature, but also related to the normalized frequency of the fibre and the order of the mode. This means, for different modes in the same waveguide, the change of effective refractive index caused by bending is different, which may

increase or decrease the effective refractive index. On the other hand, for the modes of the same order in waveguides with different normalized frequencies, the changes of effective refractive index caused by bending are also different, which may increase or decrease the effective refractive index [8]. The change of the effective refractive index of the mode has an effect on the resonant wavelength excited by the mode. The above analysis is further verified by the simulation below.

2.2. Simulation

The optical simulation discussed here was carried out by using commercially available software (Mode Solutions) to analyse the optical field intensity distribution and calculate the effective refractive index of different cladding modes in the bent fibre. The refractive index of core/cladding was set to 1.4509/1.444 respectively, and the ambient refractive index set to 1. The fibre model was established by assuming a three-layer cylindrical structure. The fundamental mode light intensity was centrally distributed in the core and almost unaffected by bending. The low-order cladding modes, LP_{03} and LP_{07} , and the high-order cladding modes, LP_{018} and LP_{019} , were selected as examples used to analyse the mode field intensity distributions under different curvatures. The results of this analysis are shown in Table 1.

Table 1 indicates that the selected low-order cladding modes, such as LP_{03} and LP_{07} , have a zero curvature when the light intensity is centrally distributed in the core (Black circle in the center of the figure) and its nearby areas. With the curvature increasing, the centre of the intensity distribution constantly moved away from the core. The selected higher-order cladding modes of LP_{01} and LP_{019} exhibit the same tendency in the curvature range of 0 to 20 m^{-1} as the curvature increases. However, in the curvature range of 20 to 40 m^{-1} the optical intensity of the light field of the selected higher-order cladding modes shows a tendency to re-coupling into the core, in a way much different from the low-order cladding modes of LP_{03} and LP_{07} .

This indicates that the variation of light intensity distribution of different modes with curvature change is different, depending on multiple effects of bending curvature, normalized frequency and mode order. From Table 1, it can be seen that the low-order cladding modes are more susceptible to bending as they have a more concentrated light intensity distribution moving away with increasing curvature. From the coupling theory, the mode light intensity distribution is related to the effective refractive index of the mode. In the curvature range of 20 to 40 m^{-1} the light intensity distribution of the selected low and high order cladding modes varies in the opposite way, indicating the effective refractive index change occurs in opposite way. The effective refractive index changes of the LP_{07} and LP_{018} modes in the 0 to 40 m^{-1} range curvature were calculated and the results shown in Figures 2 and 3.

It can be seen that the effective refractive indices of these two modes vary with the curvature change in the same direction until the value of $K = 12 \text{ m}^{-1}$, even if the high-order mode shows a smaller sensitivity over the curvature change. After this value of K , they vary with the curvature in the opposite direction. This observation verifies the predication of the modal light intensity distribution with different curvature seen in Table 1. The change of the effective refractive index of the cladding mode will affect the corresponding excitation mode resonance wavelength.

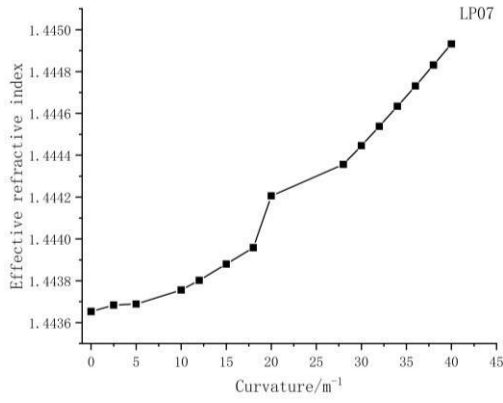


Figure 2. Effective refractive index of LP₀₇ mode vs curvature.

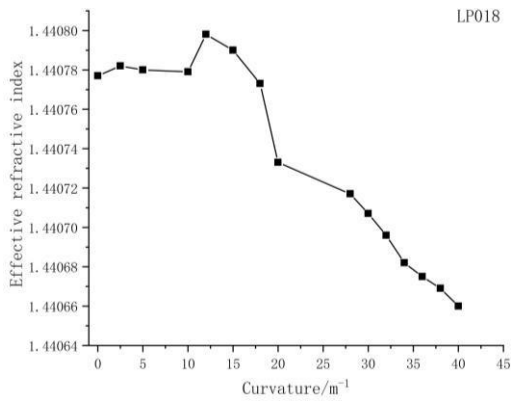


Figure 3. Effective refractive index of LP₀₁₈ mode vs curvature.

This also indicates that due to the effect of curvature, the resonance wavelengths of different mode will shift to a different direction in the grating transmission. As discussed above, the lower-order cladding modes are more sensitive to curvature and more of their light intensity distributions are seen to move away from the core, as the curvature increases. According to the calculation carried out, the low-order cladding modes in the tilted grating will shift to the long wavelength side, while the resonance wavelengths of higher-order cladding modes will shift in different way, depending on specific mode. Figure 4 simulates the variation of the LP₀₇ mode wavelength with the effective refractive index of the cladding mode. This shows that the resonant wavelength of this low-order cladding mode changes linearly with the mode effective refractive index. This important feature makes tilt gratings an ideal basis for fiber bend sensors.

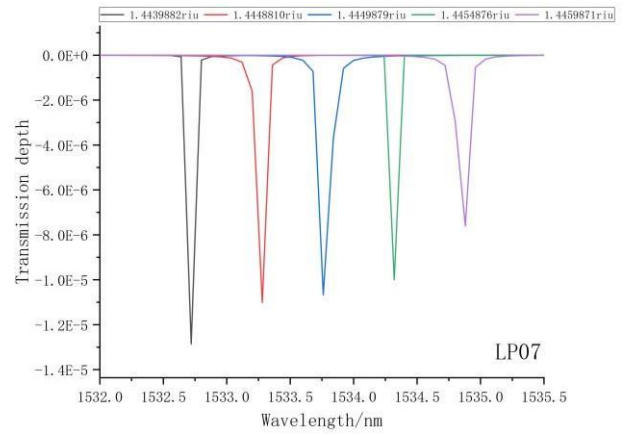


Figure 4. Simulates the variation of the LP₀₇ mode wavelength with the effective refractive index of the cladding mode.

Table 1. Simulated mode light intensity distribution with different curvature.

| Mode \ Curvature | LP ₀₃ | LP ₀₇ | LP ₀₁₈ | LP ₀₁₉ |
|----------------------|------------------|------------------|-------------------|-------------------|
| K=0m ⁻¹ | | | | |
| K=2.5m ⁻¹ | | | | |
| K=20m ⁻¹ | | | | |
| K=40m ⁻¹ | | | | |

3. EXPERIMENTAL TESTS

A 3° tilted grating is used to experimentally verify the results of the simulation carried out as the basis for the design of a better fibre optic sensor. Fig. 5 shows a schematic diagram of the measurement system. A length of the fibre with the tilted grating is looped into a ring and by changing the diameter of the ring, the radius of curvature, R , and the curvature, K , of the bent grating can be readily adjusted. The resonance wavelengths of cladding modes of tilted grating under different curvatures can be observed.

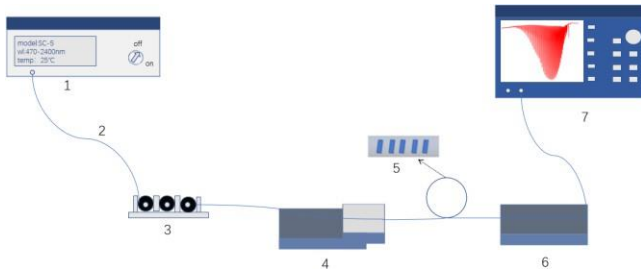


Figure 5. Schematic of experimental arrangement. 1: supercontinuum light source, 2: optical fibre, 3: polarizer controller, 4: linear translation stage, 5: tilted fibre grating, 6: fibre holder, 7: Optical Spectrum Analyser (OSA).

The light from the supercontinuum light source used is fed via the polarization controller to be coupled into the tilted grating under curvature. The radius of the ring was precisely controlled by the linear translation stage, to change the bending curvature of the grating. The transmission spectrum of the tilted grating was measured in real time by using the Optical Spectrum Analyser (OSA).

The transmission spectra of the tilted grating under curvatures of 0, 25.2 and 39.3 m^{-1} are shown in Fig. 6. It can be seen that with the increase of curvature, the intensity of lower and higher order cladding modes has altered to a different extent. The transmission intensity of the low-order cladding modes (1544nm after) is suppressed more significantly. This is because low-order cladding mode is more sensitive to the curvature change, and the light intensity distribution moves away from the fibre core, as the curvature increases.

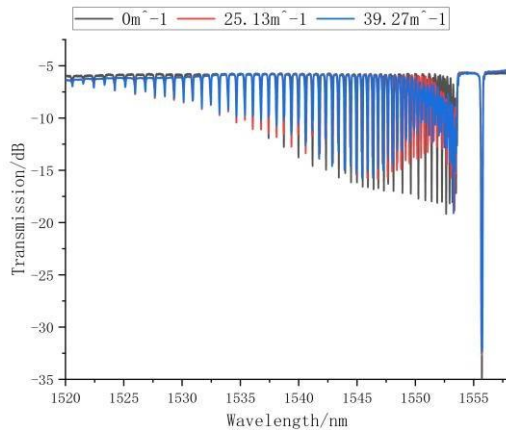


Figure 6. Transmission spectra of tilted grating under different bending curvatures.

The transmission spectra of the tilted grating under 8 different curvatures were then captured. One low-order and one high-order cladding mode situation was selected and analysed, respectively, as shown in Figures 7 and 8. It is obvious that the resonance peak corresponding to the selected two-order cladding mode has the opposite shift trend when the curvature increases. The selected low-order cladding mode whose resonance wavelength is initially at ~ 1548.45 nm was shifted toward the long-wavelength direction with curvature increasing, while the higher-order cladding mode at ~ 1540.6 nm was shifted toward the short-wavelength direction with the curvature increasing.

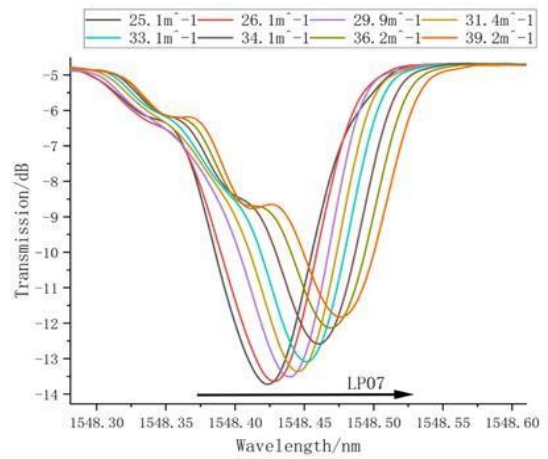


Figure 7. The resonance wavelength of the low-order cladding mode (LP₀₇) varies with curvature change.

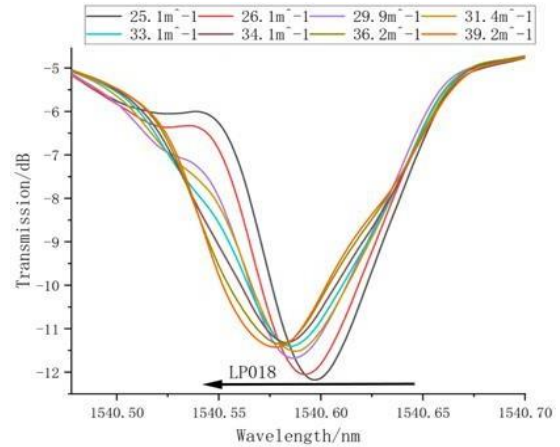


Figure 8. The resonance wavelength of the high-order cladding mode (LP₀₁₈) varies with curvature change.

It can also be noted that when subject to the bending the low-order cladding mode exhibits larger changes in resonance strength and wavelength than the high-order cladding mode, which indicates that the low-order cladding modes are the more sensitive to curvature sensing, an outcome which is in agreement with the above simulation results.

The above study shows that the low order cladding mode of the tilted grating has a good sensitivity with regard to fibre bending, making it an important feature which can be used for bending sensing. Fig. 9 shows the captured transmission spectra of the 3° tilted grating subject to the curvature from

25 to 40 m^{-1} . When the curvature increases, the lowest order of the cladding modes in the transmission spectrum is observed, whose resonance wavelength and strength vary with the curvature increasing.

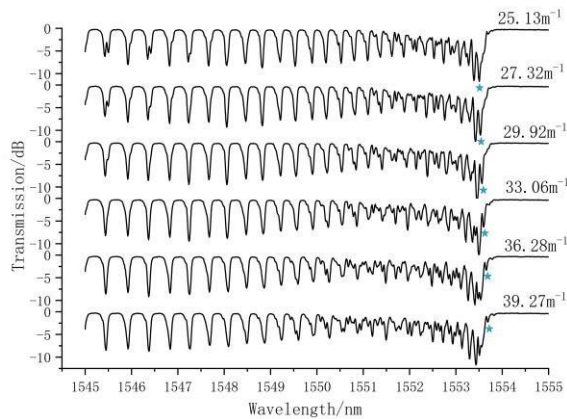


Figure 9. Captured transmission spectra of a 3° tilted grating under different bending curvature.

The resonance wavelength of this cladding mode as a function of curvature has been plotted and shown in Fig. 10. This shows a good linearity, indicating a sensitivity value of 0.01363 nm/m^{-1} . The bending curvature therefore can be determined by this resonance wavelength shift of the cladding mode in a fibre optic sensor using this effect for monitoring the degree of curvature of a structure to which it is attached.

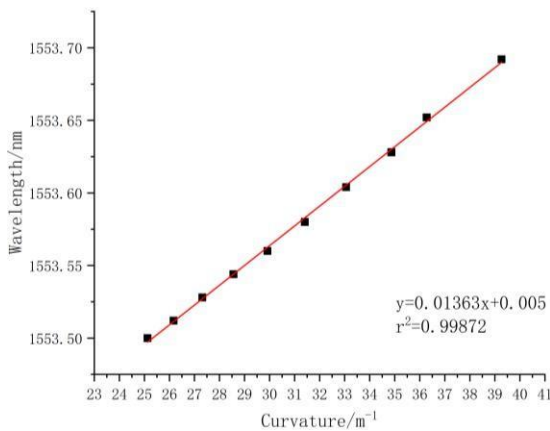


Figure 10. Resonance wavelength vs curvature.

4. CONCLUSIONS

Taking advantage of the fibre mode characteristics, it has been observed that low and high-order cladding modes of tilted grating have different behaviours under fibre bending. The light intensity distribution of the low-order cladding modes moves away from the fibre core, and the resonance wavelength has been shifted to the longer wavelength region, as the curvature increases. On the other hand, the light intensity distribution of the high-order cladding modes moves away from the fibre core, first as the curvature increases, and then shows the tendency to re-coupling into the core. This leads to the resonance wavelength first increasing, and then decreasing, with the increase in curvature. The resonance wavelength of low-order cladding modes shows a larger and a monotonic response to the bending.

Such a feature has been demonstrated for curvature measurement in an optical fibre sensor by locating the wavelength of a lowest-order cladding mode. Compared with the curvature sensing realized by measuring the intensity change of the low-order cladding mode of tilted grating, this type of sensor which uses the change in wavelength (and thus wavelength measurement) is more attractive and more reliable for a range of practical applications taking advantage of the sensitivity of the measurement. This type of sensing mechanism is of real significance for a fibre optic based device which allows accurate measurement of curvature and this has potential use in a variety of applications in engineering today.

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