Use of weakly titled fiber Bragg gratings for strain sensing purposes

C. Caucheteur[1], C. Chen[2], J. Albert[2], P. Mégret[1]

[1] Faculté Polytechnique de Mons, Service d'Electromagnétisme et de Télécommunications, Boulevard Dolez 31, 7000 Mons, Belgium

[2] Carleton University, Department of Electronics, Colonel By Drive 1125, K1S 5B6 Ottawa, Canada

Weakly tilted fiber Bragg gratings with grating planes tilted at small angles with respect to the fiber axis couple light to backward going core and cladding modes. Their transmitted spectrum is characterized by narrow resonance dips below the Bragg wavelength corresponding to the core mode coupling. We present the spectral evolution of weakly tilted fiber Bragg gratings in response to temperature changes, bending, axial strain and transversal loads. Because the cladding modes in the transmitted spectrum present different sensitivities than the core mode, the obtained results demonstrate the great potential of these gratings for temperature-insensitive strain sensing applications.

Introduction

Fiber Bragg gratings (FBG) are widely used as sensors of temperature, strain and microbending [1]. These optical sensors are compatible with structures made of composite materials; they are chemically inert and inherently immune from electromagnetic interference. However, when temperature and strain simultaneously affect an FBG, the measurement of the wavelength shift does not provide temperature-insensitive strain measurement. To discriminate these two contributions, structures such as two FBGs, superimposed FBGs, hybrid FBG with long period grating and high birefringence FBGs are required but they increase the complexity of the sensors [1].
Weakly tilted fiber Bragg gratings (TFBG) couple light both to backward propagating core mode and cladding modes [2]. The resonant wavelengths for these mode couplings depend differentially on external perturbations. This has several advantages. While the core mode (Bragg) resonance is only sensitive to axial strain and temperature, the cladding mode resonances are sensitive to the external perturbations (strain, temperature, bending, refractive index, …) [3-6].
In this paper, we analyze the evolution of the transmitted spectrum of TFBGs in response to external perturbations and we demonstrate that temperature-insensitive strain measurements are possible with such gratings.

Cladding modes coupling in TFBGs

In TFBGs, two kinds of couplings exist. The Bragg wavelength, corresponding to the self contra-propagating coupling of the core mode is given by [2]:

$$\lambda_B = \frac{2 n_{eff,core} \Lambda_g}{\cos\theta} \quad (1)$$

where $n_{eff,core}$ is the effective refractive index of the core, Λ_g is the nominal grating period and θ is the internal tilt angle (Figure 1).

The resonant wavelengths of the cladding modes, corresponding to the contra-propagating coupling between the core mode and the cladding modes, are given by [2]:

$$\lambda_{cld,i} = (n_{eff,cld,i} + n_{eff,core}) \frac{\Lambda_g}{\cos\theta} \quad (2)$$

where $n_{eff,cld,i}$ is the effective refractive index of the cladding mode i, i=1, …, m with m the total number of cladding modes.

Figure 2 presents the typical transmitted spectrum of a TFBG with the cladding modes resonances situated below the Bragg wavelength. An important feature of weakly tilted FBGs is the presence of a strong "ghost mode" resonance, immediately to the left of the Bragg resonance. This ghost mode is made up of several low order cladding modes.

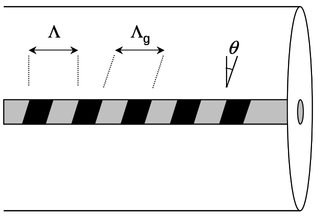

Figure 1. Schematic of a TFBG.

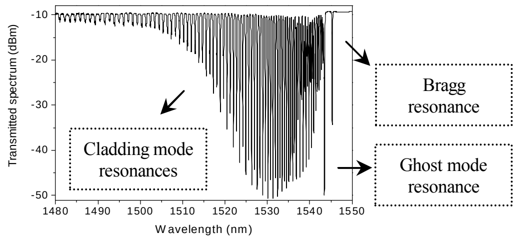

Figure 2. Transmitted spectrum of a 3° TFBG.

The experimental results presented below were obtained on TFBGs inscribed into standard single mode fiber using a pulsed laser (KrF – 248 nm) and a phase mask.

Temperature and axial strain influences on the transmitted spectrum

Figures 3 and 4 show the relative wavelength shifts of cladding modes resonances with respect to the Bragg resonance when axial strain and temperature affect a 4° TFBG. 3 differential wavelength shift regions are obtained for the strain perturbation. First, the ghost mode region appears to be very sensitive to external strain perturbations while low order cladding modes (up to 5 nm from the Bragg wavelength) have negative relative wavelength shifts. Secondly, between 5 nm and 20 nm from the Bragg resonance, the differential wavelength shift grows very linearly with mode order and with strain.

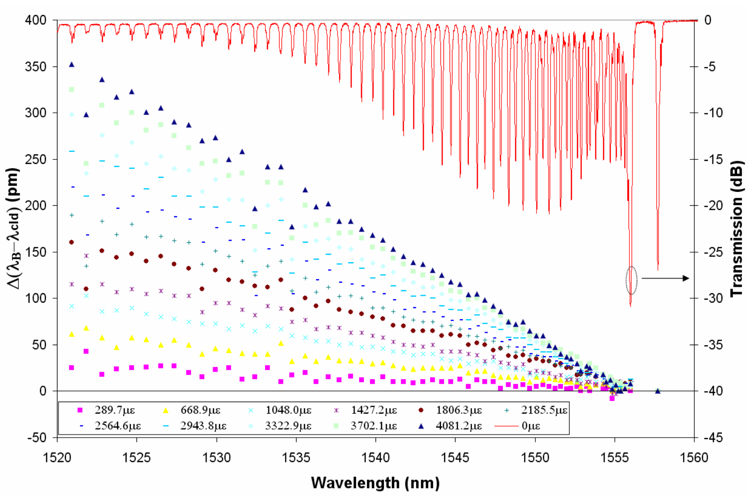

Figure 3. Transmitted spectrum of a 4° TFBG and differential wavelength shift due to strain changes.

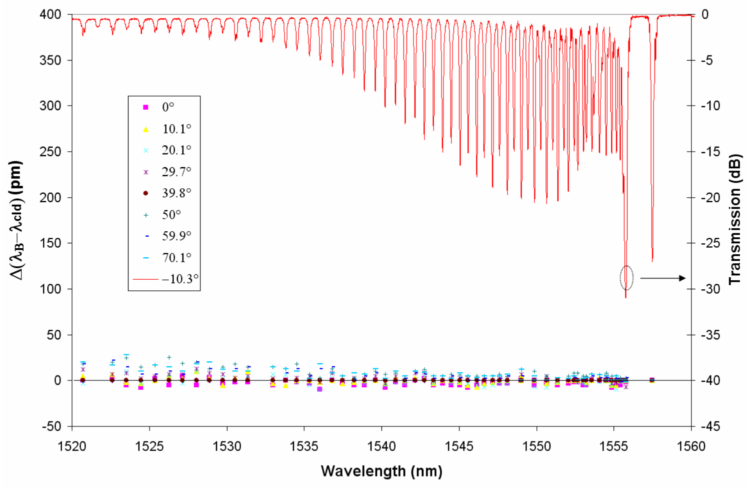

Figure 4. Transmitted spectrum of a 4° TFBG and differential wavelength shift due to temperature.

For higher order modes, further than 20 nm from the Bragg resonance, the results become irregular because the cladding mode resonances have double- and triple-peaked resonances which are difficult to follow reliably over large shifting ranges. If the same individual peak of a multi-peak resonance could be followed unambiguously, then the differential wavelength shift should continue to be linear.

On Figure 4, within the temperature range from about -10°C to 70°C, the relative cladding mode shifts are less than ± 12 pm or equivalent to an apparent ± 1.2°C drift in over ~80°C of temperature variation (except for the short wavelength region). Therefore, a temperature insensitive sensor can be made by monitoring the relative core and cladding mode wavelength shifts in the transmission spectrum.

Bending and transverse strain influences on the transmitted spectrum

Figure 5 presents the effect of a curvature on the transmitted spectrum of a 1 cm long 3° TFBG whereas Figure 6 presents the effect of a transversal load on the transmitted spectrum of a 1 cm long 4° TFBG. Unlike temperature and axial strain effects, curvatures and transversal loads affect the peak to peak amplitudes of the resonances in the transmitted spectrum. The bending mainly influences the cladding modes near the ghost mode region while transversal loads affect the whole spectrum.

In order to efficiently correlate the spectral evolution with the external perturbation, a global measurement of the area delimited by the cladding modes in the transmitted spectrum was privileged in comparison to a local detection of the cladding modes [6,7].

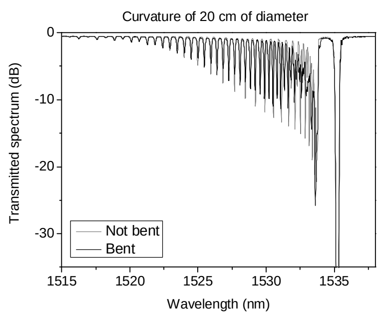

Figure 5. Effect of a curvature on the transmitted spectrum of a 3° TFBG.

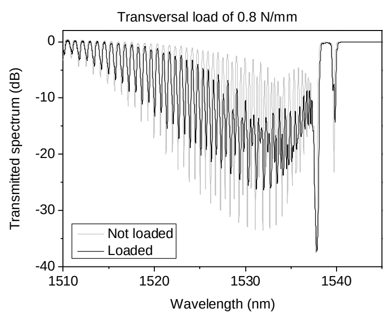

Figure 6. Effect of a transversal load on the transmitted spectrum of a 4° TFBG.

Figures 7 and 8 present the evolution of the normalized area (ratio between the area delimited by the perturbed spectrum and the reference area) in response to bending and transversal loads, respectively. In both cases, the evolution is monotonic and decreasing. We experimentally verified that the temperature influence on the value of the normalized area in the range -10°C to 70°C can be neglected. This behavior was expected since all the cladding modes present nearly the same temperature sensitivity. They are thus all shifted without significant modification of the area delimited by the cladding modes. This property provides temperature-insensitive bending and transverse strain measurements. Let us also mention that the Bragg resonance is not affected by the bending, which is not the case for transversal loads.

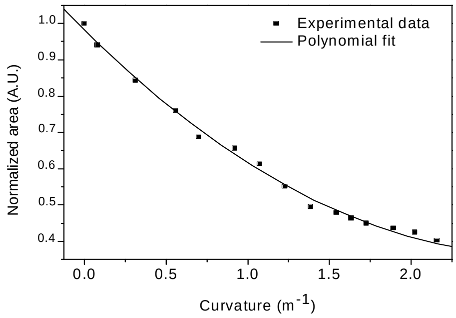

Figure 7. Evolution of the normalized area versus curvature for a 3° TFBG.

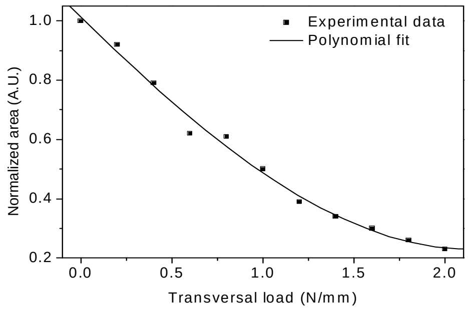

Figure 8. Evolution of the normalized area versus transverse strain for a 4° TFBG.

Conclusion

In this paper, we demonstrated that weakly tilted fiber Bragg gratings can be advantageously used for temperature-insensitive strain sensors. To measure the axial strain, a local measurement of the cladding modes was chosen whereas to measure the bending and the transverse load, a global measurement of the area delimited by the cladding modes was privileged. In both cases, a good sensitivity was obtained.

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