Modulation of coaxial modal interferometers based on long period gratings in double cladding fibers

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Abstract: This paper reports on the dynamic modulation of coaxial interferometers based on two cascaded long period gratings written in double cladding fibers. The interferometer is modulated by a piezoelectric ceramic which stretches one the gratings at tens of kHz, the output light is intensity modulated with an efficiency of 97 %. The device operates at 1530nm, has more than 50nm bandwidth, insertion loss of 0.4 dB and a temperature drift of 0.11 nm/°C.

OCIS codes: (060.4080) Modulation; (060.0060) Fiber optics; (050.2770) Gratings; (140.0140) Lasers and laser optics.

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1. Introduction

A fiber long period grating is a periodic modulation of the fiber refractive index that couples energy between core and cladding co-propagating modes [1]. The grating behaves as a notch filter and has several applications such as shaping the spontaneous emission of Erbium doped fibers [2], measurement of physical magnitudes or chemicals detection [3, 4]. Two concatenated long period gratings behave as a Mach-Zehnder interferometer, the first grating couples energy from the core guided mode to a cladding mode, and the second grating couples energy between both modes producing the optical interference [5]. These coaxial interferometers have found applications in wavelength division multiplexing and sensors [6,7,8]. The main inconvenience of devices based on long period fiber gratings arises from the sensitivity of the cladding mode to the refractive index of the surrounding medium. To prevent this problem, long period gratings have been fabricated in three layered optical fibers, whose inner cladding modes are immune to the external index [9, 10, 11].

Double cladding fibers are currently being used in cladding pumped fiber lasers and amplifiers, the development of intensity modulators in these fibers might give rise to compact Q-switched high power lasers. In this paper we present, to the best of our knowledge, the first Mach-Zehnder interferometer made with long period gratings in double cladding fibers; the interferometer can be dynamically modulated by a piezoelectric ceramic and has a reasonable temperature stability apart from being insensitive to the refractive index of the external medium.

2. Experiment and results

A three layer silica based fiber provided by Fibercore Ltd. (product number SMM980) was used in this experiment, the fiber has an outer diameter of 125.1 μm and an inner cladding diameter of 88.3 μm; the singlemode waveguide has a cut-off wavelength of 964 nm and a numerical aperture of 0.20 while the multimode waveguide has numerical aperture of 0.23. The fiber core is a photosensitive germano-silicate glass and the two cladding layers are transparent to the ultraviolet radiation. The core sensitivity was enhanced soaking the fibers in pressurised hydrogen for two weeks at 30 bar and room temperature. Gratings were fabricated step by step with a doubled argon laser focused over the fiber through a 25 μm width slit, the laser beam was shut each half period; the scanning speed was of the order of 0.2 mm/min and gratings are fabricated in few minutes time.

A strong grating was fabricated in this fiber before making the interferometer in order to identify the modes to which energy is coupled. The grating had a period of 120.5 μm and a length of 11.5 mm which was optimized for maximum coupling at 1522 nm. The grating spectrum of Fig. 1 shows the coupling to cladding modes. Maxwell equations with boundary conditions were solved for a four layer waveguide in order to calculate the propagation factor of core, inner cladding and outer cladding modes; afterwards, the resonant wavelengths of a grating were calculated as a function of the grating period, the results are shown in Fig. 2. The resonances of two gratings fabricated with different periods are fitted onto the theoretical curves, these results reveal that the transmission notches of Fig. 1 correspond to inner cladding modes from LP_{02} to LP_{010}.

Gratings were soaked in liquids of different refractive indices and no spectral variations were observed. A small ripple has been systematically observed in the spectrum of the gratings we have fabricated, this ripple may be an interference produced by the light coupled between core and cladding at the splices between the double cladding fiber and the singlemode input and output fibers.

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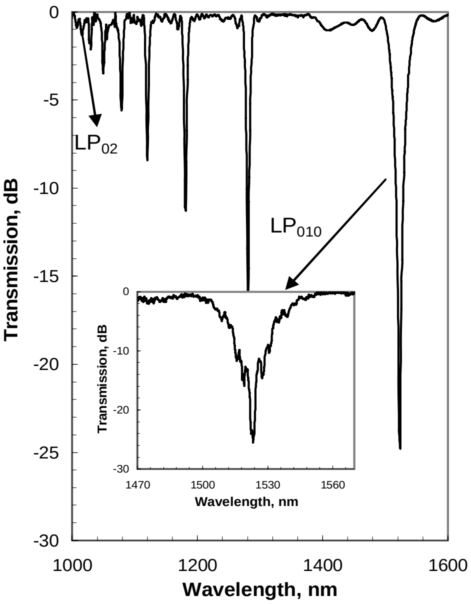

Fig. 1. Spectrum of a grating of 11.5 mm length and 120.5 μm period. The inset shows a detail of the 1530 nm notch.

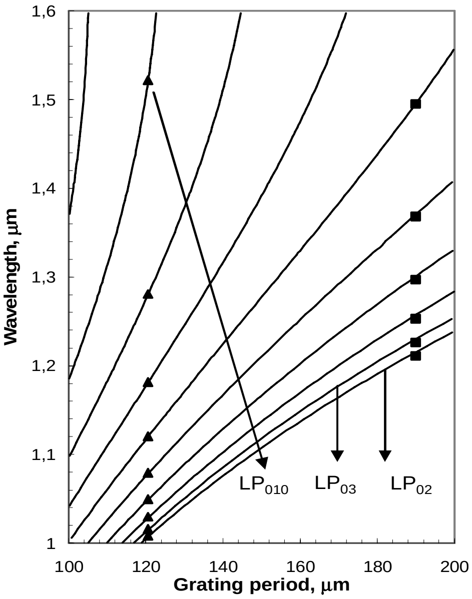

Fig. 2. Resonant wavelength of different modes as a function of the grating period. Solid line: theory. Dots: experimental results; triangles: 120 μm period grating; squares: 190 μm grating.

The grating spectrum was measured for two weeks after fabrication in order to monitor the re-diffusion of the un-reacted hydrogen, the spectral evolution of two resonances is shown in Fig. 3. Measurements show that gratings are unstable as written; initially, they experience a fast wavelength increment followed by a slow down shift. Similar results have been reported in gratings written in different conditions in standard telecommunication fibers [12]. According to this behavior, cascaded gratings must be written in a short period of time for optimum matching between their resonances. After stabilization the grating was thermally annealed at 50 ^{0}C for 24 h to remove the unstable defects at low temperature, no significant variations were observed in this process.

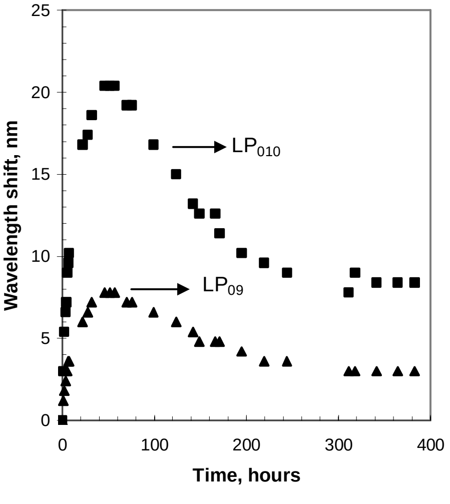

Fig. 3. Evolution of LP_{09} and LP_{010} resonances after grating inscription.

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The interferometer was made with two identical gratings of 120.5 μm period. The length of the first grating (6.24 mm) was optimized to couple 50 % of the energy to the LP_{010} mode. This resonance had a large bandwidth (about 60 nm at 1.5 dB) because of its small coupling strength. A second grating of identical period and length was written 9.2 cm apart; the device had a total length of 10.45 cm, an schematic diagram is shown in Fig. 4. The transmission spectrum of the interferometer is shown in Fig. 5, it consists of a set of transmission bands whose bandwidth increases with wavelength from 3.5 nm at 1480 nm to 7.7 nm at 1600 nm, the central fringe at 1530 nm has a bandwidth of 4.2 nm and an amplitude of 16 dB. The spectrum was measured with 0.5 nm resolution using an optical spectrum analyzer and a luminescent diode as light source. The insertion loss of the device, measured on the tops of the transmitted bands, is less than 0.4 dB (splice loss is excluded from this figure). Resonances of modes LP_{08} and LP_{09} were also observed, but their interference patterns had poorer visibility than mode LP_{010} because they couple less energy than 50 % between core and cladding; no coupling has been observed to modes of order lower than LP_{08}. It must be noted that the ripples that appear in the spectrum of the each individual grating do not have any significant effect in the interferometer performance.

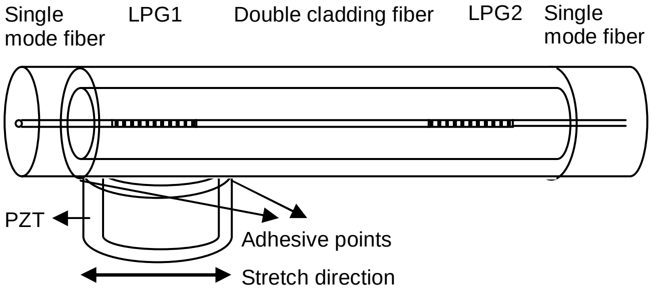

Fig. 4. Diagram of the interferometer. LPG: long period grating, PZT: piezoelectric tube.

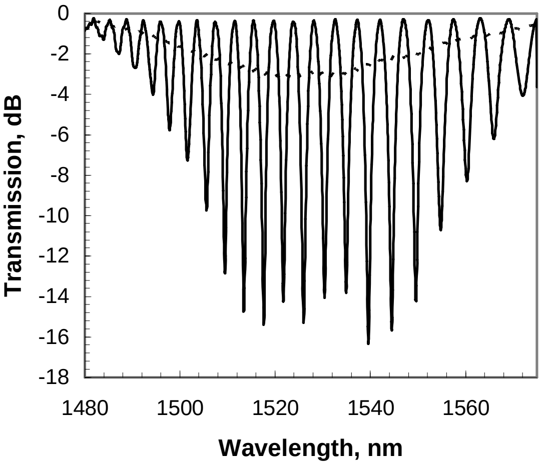

Fig. 5. Spectrum of the interferometer (solid line) and spectrum of one of the gratings (dashed line).

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The interferometer was thermally annealed and, afterwards, characterised in temperature and strain. The wavelength shift of the central interferometric fringe was measured as function of temperature and strain, results are shown in Fig. 6. The thermal sensitivity of the interferometer is positive and increases its value with the mode order, modes LP_{09} and LP_{010} have a temperature induced shift of 0.03 and 0.11 nm/^{o}C respectively. The response to axially applied forces is more complex. Mode LP_{010} has a positive response to axial strain, its sensitivity has been measured to be 30.5 nm/%ε; however, mode LP_{09} is nearly insensitive to strain, and mode LP_{08} has a negative sensitivity of -3.39 nm/%ε. This change of sign has also been reported in gratings made in single cladding fibers [13], it occurs because the differential stress-optic coefficient of core and cladding modes takes a value close to -1 for mode LP_{09} at its resonant wavelength (1280 nm).

Since the edge of the transmitted bands is relatively sharp (2.1 nm at 1530nm), it becomes possible to modulate the light transmitted by the interferometer using commercial piezolelectric or magnetostrictive transducers at frequencies of few tens of kHz. Furthermore, the interferometer has a large number of transmission bands that can be finely tuned by temperature or static strain within their free spectral range, therefore, it might be used for modulation or Q-switching lasers in a large wavelength range.

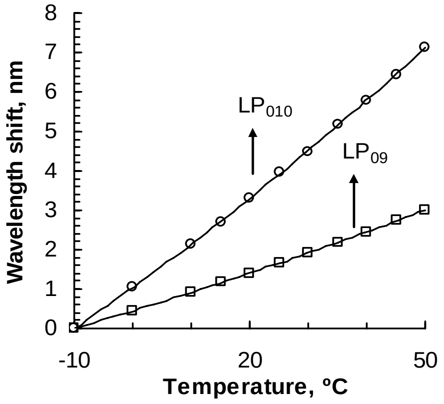

Fig. 6. (a) Thermal response of the interferometer.

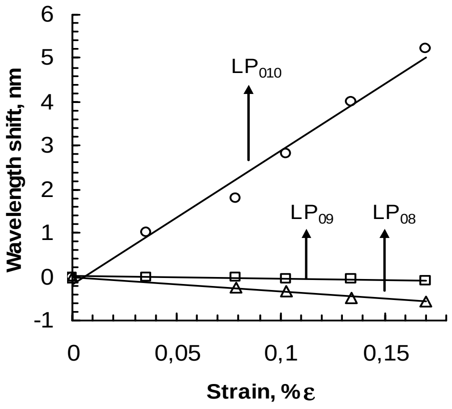

Fig. 6. (b) Mechanical response of the interferometer.

The interferometer was modulated by a piezoelectric tube placing the fiber across the tube diameter and sticking two points on the walls of the tube as it is illustrated in Fig. 4. The PZT tube was 7 cm in length and its inner and outer diameters were 4 and 5 cm respectively. The input grating as well as 3 cm of the interferometer cavity were held between the tube walls; when the transducer stretches the fiber it modifies the fiber length and its refractive index, hence, it modulates the phase difference between the core and the cladding modes. The transducer was driven with a low voltage signal at 28.3 kHz. The interferometric fringe at 1530 nm was used to modulate the light emitted by a tunable laser. Fig. 7 shows the output modulated light for three positions of the laser line with respect to the interferometric fringe. The output light is modulated at the high power level when the laser wavelength is set close to the top of the fringe, the second harmonic can be observed in the modulation curve because the top of the fringe crosses the wavelength of the laser. If the laser wavelength is close to the bottom of the fringe then the output light is modulated at the low transmission level and the second harmonic can be observed again. If the laser wavelength is optimized in the centre of the fringe, the output light is symmetrically modulated with an efficiency of 97 %, this value is in agreement with the fringes visibility of Fig. 5. Similar results were obtained when the PZT tube was placed in the cavity of the interferometer instead of holding the grating.

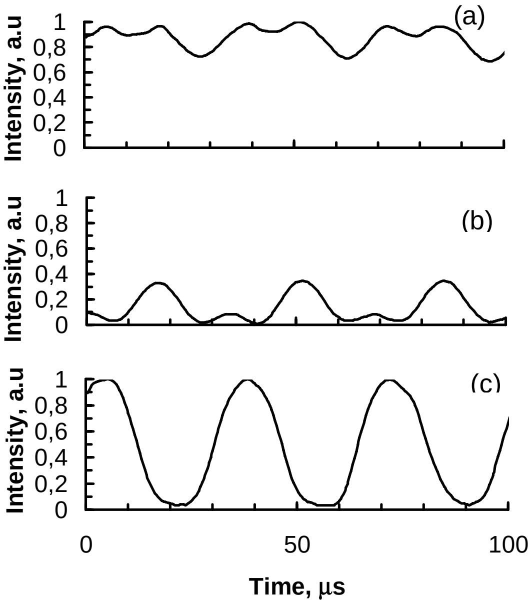

Fig. 7 Modulated light at different relative positions of the laser line: (a) Laser line on the top of the interferomertic fringe fringe. (b) Laser in the bottom of the fringe. (c) Laser in the center of the fringe.

Fiber interferometers are polarization sensitive because of the residual birefringence of the fibers; furthermore, photo-inscribed gratings have a slight anisotropy inherent to the fabrication process and, as a result, the gratings response has some dependence on the polarization state. Polarization effects have been analyzed and it has been found that each band pass shifts about 0.1 nm when the input polarization state is scanned, this variation is negligible in this interferometer. However, we have fabricated 2 m long interferometers which have a peak spacing below 0.18 nm, in these interferometers the input polarization state has notable effects both in the visibility and in the wavelength position of the fringes. These long interferometers are difficult to handle because they must be kept in straight line in order to avoid coupling between modes in the multimode waveguide, furthermore they can not be operated with un-polarized light.

3. Conclusion

Efficient modulation of light has been achieved at frequencies of tens of kHz using coaxial interferometers made with long period gratings in double cladding fibers. An interferometer 10.45 cm long with a peak spacing of 4.2 nm has been fabricated, it can be used in a wavelength range of 50 nm around 1530 nm; the interferometer has low insertion loss, low sensitivity to the input polarization state, negligible dependency on the refractive index of the surrounding media and a thermal sensitivity of 0.11nm/^{o}C.

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