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Ring fibre laser with interferometer based in long period grating for sensing applications

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ABSTRACT

This work presents two distinct configurations based on phase–wavelength conversion using a ring fibre laser with two different long period gratings interferometer topologies. The sensors are interrogated by analysing the wavelength change of the emission laser, which is directly dependent on the interferometer phase change. The first configuration integrates a Mach–Zehnder interferometer, which is based on a pair of long period gratings and is used as sensing head for bending radius and longitudinal strain measurement. The second configuration, comprehends a Michelson interferometer, which is based on a single LPG and a fibre end mirror and is used as a liquid level sensor or as an optical refractometer.

1. Introduction

Long period gratings (LPGs) are formed by imposing a periodic perturbation on a single mode fibre, with an interval in the order of hundreds of microns, causing light coupling from the fundamental core mode to the cladding modes. This effect creates more sensitivity to external perturbations, which brings a variation in the optical power and/or a shift in the wavelength notches. LPGs are optical devices that work as band rejection optical filters and can be also used as optical sensors. LPG based sensors measure different physical parameters, namely, temperature, strain, curvature and refractive index [1].

LPGs can also be used to implement versatile fibre mode interferometers with enhanced parameter sensitivity. This is done by cascading within a certain fibre length two similar LPGs, resulting in a Mach–Zehnder configuration. For the interferometer operation the first LPG couples part of the light to one of the cladding modes, where it propagates with an effective refractive index smaller than the one experienced by the light that propagates in the core. The cladding light is recoupled in the second LPG. In this way, a differential optical-path length is accumulated between the two light waves. A work based on this type of interferometer was monitored by a conventional technique using a broadband source and also an optical spectrum analyzer for transverse load, curvature and refractive index measurements [2]. The authors have demonstrated that the Mach–Zehnder interferometer has a non linear behaviour when the sensing head is subjected to curvature. On the other hand, Allsop et al. have reported a curvature sensor using a LPG written in a D-shape optical fibre. In this case, the curvature sensing presents a linear response when compared with standard optical fibre [3]. Another type of interferometer is the Michelson interferometer and consists in a single LPG and a mirror. In this case the cladding light recouped for the same LPG. This interferometer was explored by Lee and Nishii [4] to implement a temperature sensor and by Swart [5] to aim refractive index measurements.

Other applications use cascaded LPGs as an optical filter in ring fibre lasers. The advantage of the optical filter based on this technology is to control the wavelength spacing of the spectral response through the length between two LPGs. Yan et al. have proposed a triple-wavelength switchable erbium-doped fibre laser with cascaded LPGs [6]. Zhao et al. reported a configuration for automatic gain control of optical amplifiers using a phase-shift LPG, where the distance between the two LPGs is equivalent to the grating period of the LPG. The gain control was obtained by curving the phase-shift LPG device [7].

This paper presents two phase–wavelength conversion configurations using a ring fibre laser contained interferometer based on long period grating technology. The first configuration integrates a Mach–Zehnder interferometer, which is based on a pair of long period gratings and is used as sensing head for bending radius and longitudinal strain measurement. The second configuration, comprehends a Michelson interferometer, which is based on a single LPG and a fibre end mirror and is used as a liquid level sensor or as an optical refractometer. This work intends to demonstrate an alternative interrogation technique for reading these types of interferometers when used as optical fibre sensors. The ring fibre

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laser contains the interferometers that work as a sensor and at the same time as filters that stabilize the laser emission. When physical parameters are applied, the phase of the interferometers is changed and the wavelength of the laser also changes.

2. Experimental results

Before assembling the Mach–Zehnder interferometer formed by the two LPGs in the ring fibre laser, the interferometer was illuminated by a broadband source and the spectral response was read by an optical spectrum analyzer. Fig. 1 presents the optical spectrum of the Mach–Zehnder interferometer. The wavelength spacing of the pattern fringe is about 10 nm. When subjecting the LPGs to curvature, a wavelength shift is observed as well as a decrease of the notches' amplitude. This reduction on the amplitude of the notches is a result of the attenuation bands that appear in the interferometer. The LPGs were written in a SMF-28 fibre using the electric arc-discharge technique. The two LPGs are identical with a period of $\Lambda = 395\ \mu m$ (57 arc discharges each), and are located apart by 70 mm centre to centre. This separation length was chosen intentionally to have a single laser emission peak when inserted in the ring fibre laser configuration.

Fig. 2 shows the first experimental setup of the ring fibre laser sensor comprehending the Mach–Zehnder interferometer. The laser system consists on a commercial erbium-doped fibre amplifier (EDFA) followed by a polarization controller, a pair of LPGs to form the Mach–Zehnder cavity and an optical coupler with a ratio of 80:20, where 80% of the signal stays on the loop and 20% is monitored by an optical spectrum analyzer with a resolution of 0.05 nm. This configuration enables to convert the change of the phase of the interferometer in a change of the wavelength laser when the sensing head is subjected to bending or longitudinal strain.

Before subjecting the sensing head to bending, the LPGs were kept horizontally flat and the spectral response of the fibre ring laser was characterized. The polarization control was adjusted in order to obtain only one peak at the laser output with maximum amplitude. Fig. 3 shows the resulting optical spectral response of the fibre ring laser. The output peak of the ring fibre laser presented a central wavelength of ~1529 nm, with a linewidth of

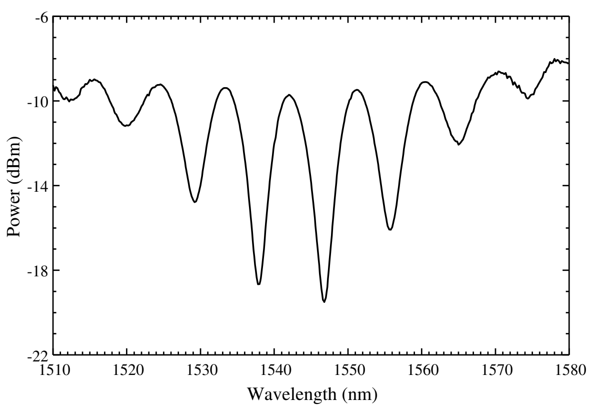

Fig. 1. Optical spectrum of the Mach–Zehnder interferometer.

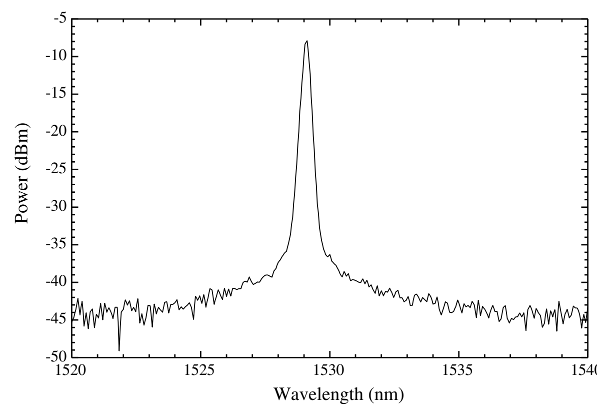

Fig. 3. Optical spectrum of the ring fibre laser.

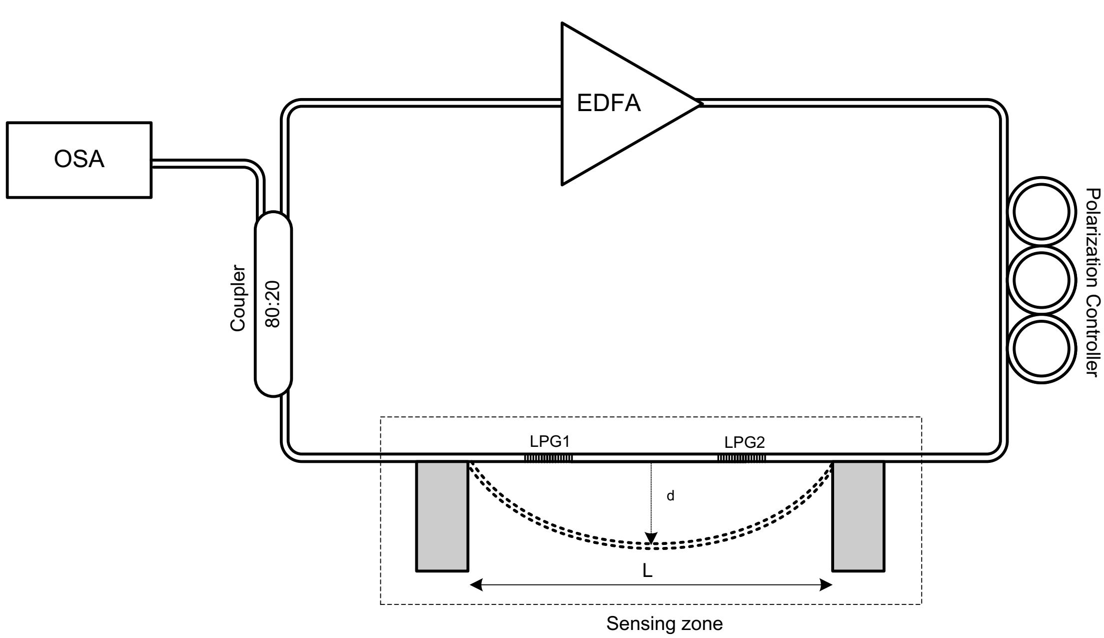

Fig. 2. Experimental setup of the fibre ring laser using a Mach–Zehnder interferometer.

∼200 pm and a peak power of −8 dBm. The signal to noise ratio (SNR) was larger than 30 dB.

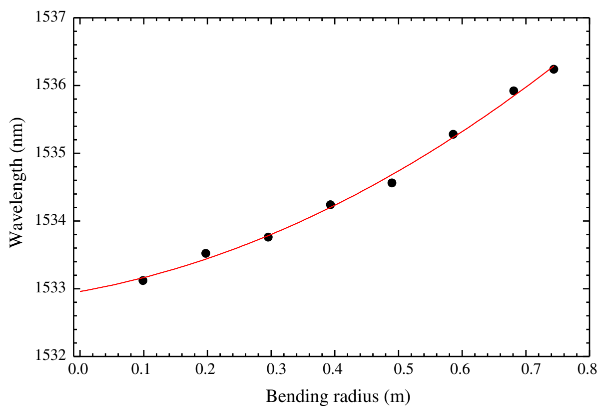

Fig. 4. Wavelength response of the sensor when is subjected to bending.

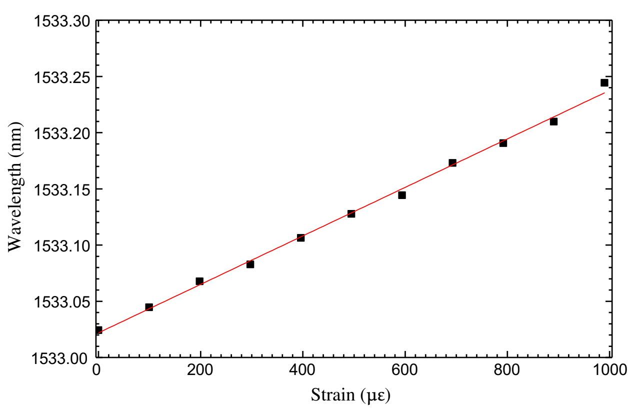

Fig. 5. Wavelength response of the sensor when the strain is applied.

The curvature sensitivity of the ring fibre laser with a pair of LPGs was studied using the experimental setup shown in Fig. 2. The sensing head was held between two fibre holders and to induce bending; one of the holders had a translation stage in the longitudinal direction. The LPGs were located in the centre of the sensing zone (see Fig. 2). In order to estimate the bending radius the following equation was used [8] $R = 2d/(d^2 + L^2)$, where d is the distance of the sensor from the flat horizontal position and L is the distance between the edges of the two fibre holders. The initial distance between the holders was 400 mm.

Different curvatures were applied to the sensing head by displacing the translation stage inwards in the longitudinal direction. For each bending radius, the optical spectrum of the wavelength shift of the ring fibre laser was taken (Fig. 4). The obtained laser emission wavelength variation results from the phase change of the interferometer with the applied bending, which is a result of an increase of the optical paths difference of the interferometer. As it can be seen in Fig. 4, when bending is applied, the sensing head presented a nonlinear response to wavelength shift.

In order to measure longitudinal strain the sensing head was initially stretched and strain was applied by displacing the translation stage outwards. Fig. 5 shows the response of the sensing head when strain is applied. The response is linear and presents a strain sensitivity of −0.02 nm/mm.

The second configuration implemented in this work is presented in Fig. 6. It shows the other experimental setup where the Mach–Zehnder interferometer was replaced by a circulator and a Michelson interferometer. The Michelson interferometer has a length of 100 mm between the LPG and the mirror. Fig. 7 shows the response of the interferometer for different liquid levels. It is a linear response and the presented coefficient sensitivity relatively to the liquid level of −0.02 nm/mm. Fig. 8 shows the response of the Michelson interferometer when subjected to different refractive index liquids. In this case the level liquid was maintained constant (50 mm). These two responses are expected due to the refractive index of the liquids change the path length and the phase of interferometer is also changed.

The two ring configurations here presented, based on phase–wavelength conversion are an alternative solution to read Mach–

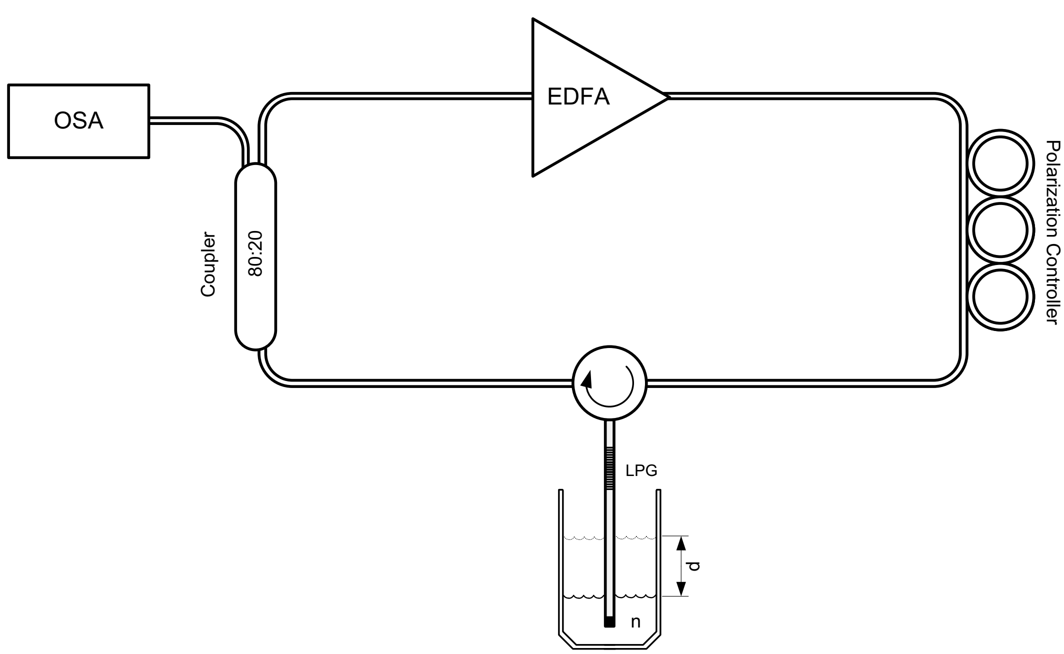

Fig. 6. Experimental setup of the fibre ring laser using a Michelson interfeormeter.

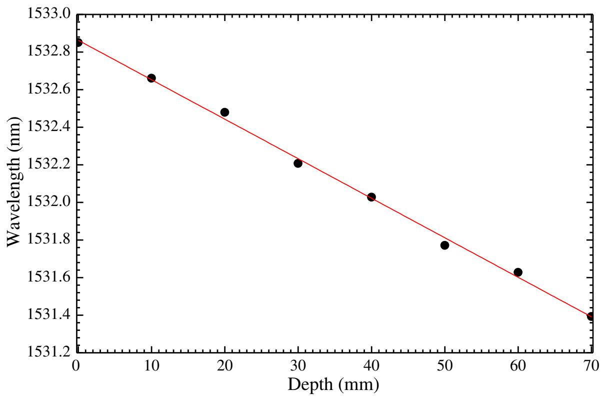

Fig. 7. Response to liquid levels.

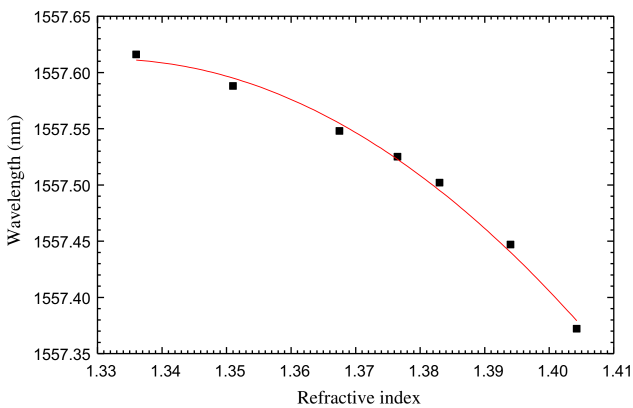

Fig. 8. Response to liquids refractive indices.

Zehnder and Michelson modal interferometers when subjected to physical parameters. The wavelength can be easily converted in an intensity sensor using a linear filter and a simple processing signal. In this case, the measurements are obtained by a simple photodetector.

3. Conclusion

In this work, we have reported two distinct configurations based on phase–wavelength conversion using a ring fibre laser with two different long period gratings interferometer topologies. Using the phase–wavelength conversion it is possible to interrogate a sensing head when the interferometers are subjected to different physical parameters. Four different physical parameters were tested using this phase–wavelength conversion technique and are similar in terms of results when compared with other works in the literature. The advantage of the phase–wavelength conversion is that the ring fibre laser response is given by a narrow peak wavelength, which can be interrogated as an intensity sensor using a linear filter.

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