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LETTER

Torsion sensor based on a figure-of-eight cavity fibre laser

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Abstract
A figure-of-eight based fibre laser cavity is proposed for the measurement of torsion. In one of the loops a section of photonic crystal fibre is inserted, acting both as an optical filter and the sensing head. The laser emission depends on the optical filter polarization and length. A single lasing band is achieved with a full width at half maximum of ∼1.72 nm. The proposed sensor presents sensitivity to torsion of 7.13 pm/degree over a range of 180°. This configuration can also be used to measure optical power variations. Besides, due to the properties of the optical filter this sensor presents low sensitivity to temperature.

(Some figures may appear in colour only in the online journal)

1. Introduction

Ring-based laser cavities have been widely explored in the past. When compared to linear cavities, the unidirectional travelling wave obtained eliminates both the backscattering and the spatial-hole burn effects [1]. Thus, these cavities present good stability, flexibility and are easy to manufacture [2].

Optical fibre lasers with a figure-of-eight configuration have been reported for multi-wavelength emission using both erbium-doped fibre [3] and erbium–ytterbium co-doped fibre [4–6] as the gain medium. The inclusion of an optical filter in the loop can be decisive in achieving good output stability [7]. Zhou *et al* reported the insertion of a filter in a ring cavity to generate four-wavelength emission with equal frequency [1]. With this configuration, dual-wavelength lasing action was also attained. The use of a twin-core photonic crystal fibre (PCF) to create a Mach–Zehnder interferometer was reported by Kim *et al* to obtain a wavelength selective comb filter [8]. Tan *et al* observed that when a PCF section was introduced into the cavity, higher output and more lasing wavelengths could be achieved [9].

Furthermore, PCFs have been explored as passive torsion sensors, proving to be sensitive to this measurand and insensitive to temperature and strain [10]. Thus, when combining both sensing and lasing properties, high resolution, small loss and low cost systems can be achieved [10, 11].

In the context of active sensors, Shi *et al* presented a Mach–Zehnder interferometer formed by a pair of long period gratings inserted in a ring laser to perform active torsion measurements [12]. Wei *et al* [13] proposed a photonic crystal fibre-based fibre ring laser with high torsion sensitivity for a small angular range.

In this letter, a laser cavity based on the figure-of-eight configuration is presented to perform torsion measurements. A section of commercial PCF is inserted into one of the loops, acting both as an optical filter and as the sensing head. The torsion will induce a modification in the sensing head cores, and it can be applied over a range of 180°.

2. Experimental results

In a first stage of this work, the interferometric filter was designed to provide the proper characteristics to be used in

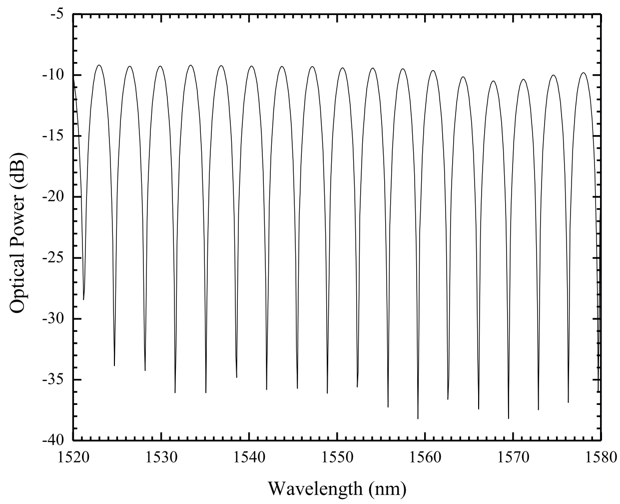

Figure 1. Optical spectrum of the interferometric filter.

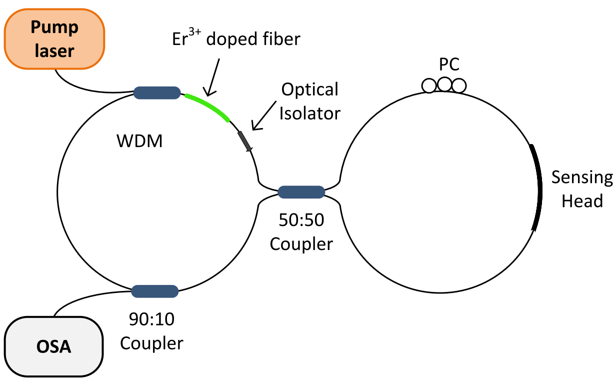

Figure 2. Scheme of the experimental setup.

Table 1. Properties of the interferometric filter (FWHM, full width at half maximum).

	Average value
FWHM (nm)	1.72
Channel spacing (THz)	0.43
Channel pass-band (THz)	0.17

the figure-of-eight configuration. The filter was made up of 78.6 cm long polarization maintaining (PM) PCF section. The PM PCF used in this experiment was a commercial one (PM-1550-01 from Thorlabs). The channelled spectral behaviour can be seen in figure 1. The main properties of this interferometric filter are gathered in table 1.

The experimental setup, presented in figure 2, had a figure-of-eight configuration. One of the loops was made up of a pump diode laser emitting at 980 nm, a 980/1550 nm wavelength division multiplexer (WDM), an optical isolator, a 90:10 optical coupler and an optical spectrum analyser (OSA) to perform the readings. In between the WDM and the optical isolator, a section of erbium-doped fibre (about 80 cm long) was inserted to provide the gain. The concentrations of the erbium and aluminum ions were 1000 ppm and 10 000 ppm, respectively. The numerical aperture of the erbium-doped fibre was 0.27, its core diameter was ~5 μm and it presented a step index profile. The other loop had a polarization controller (PC) and the interferometric filter previously described, which was used as a sensing head. Depending on the polarization of light travelling inside this loop, one or more lasing peaks were obtained. Since this configuration was used to measure torsion variations, one single peak laser was considered throughout the experiment. In between the two loops there was a 3 dB optical coupler.

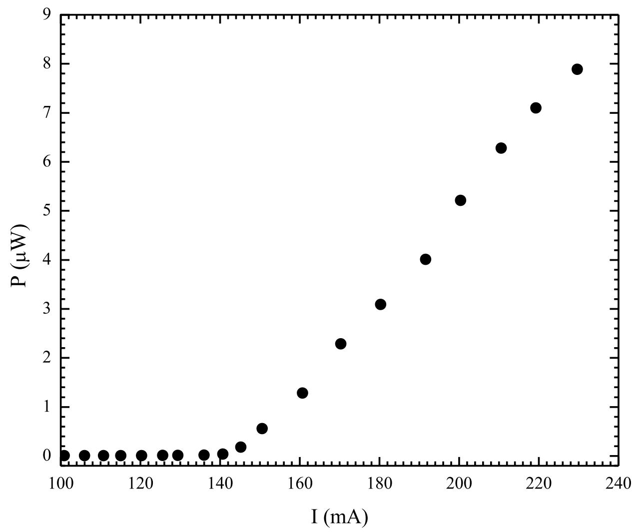

Figure 3. Optical power variations with drive-in current.

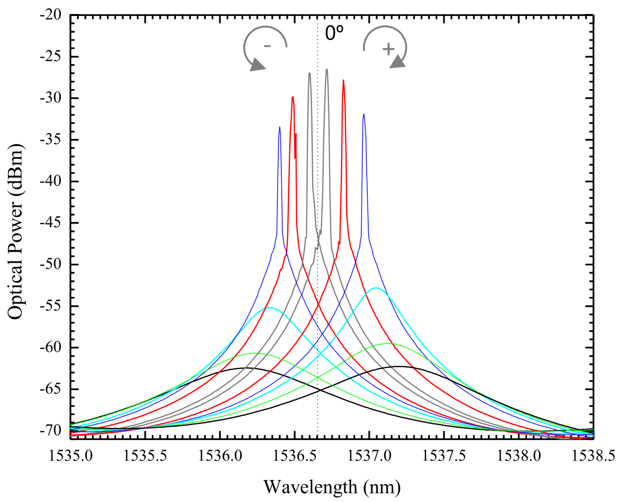

Figure 4. Variation of the laser emission with the applied torsion.

The response of the laser power to the diode drive-in current is shown in figure 3. The current threshold was estimated to be 145.5 mA and a maximum power of ~7.9 μW was achieved for a drive-in current of ~230 mA.

In order to perform torsion measurements, one side of the sensing head was introduced in a torsion stage, with a resolution of 0.5°, while the other was kept fixed. It was found that both the amplitude and central wavelength of the laser peak shifted as torsion was applied, both for positive and negative angles. This behaviour, which can be observed in figure 4, occurs due to rotation of the PM PCF cores. Starting from 0°, as the angles increased the peak shifted towards

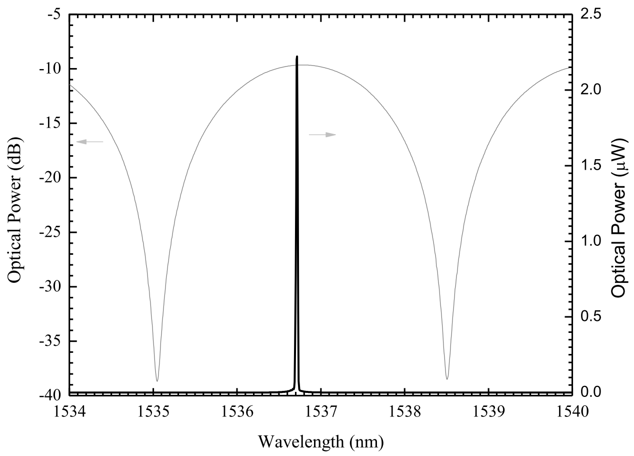

Figure 5. Interferometric filter spectrum (grey line) and laser spectrum (black line).

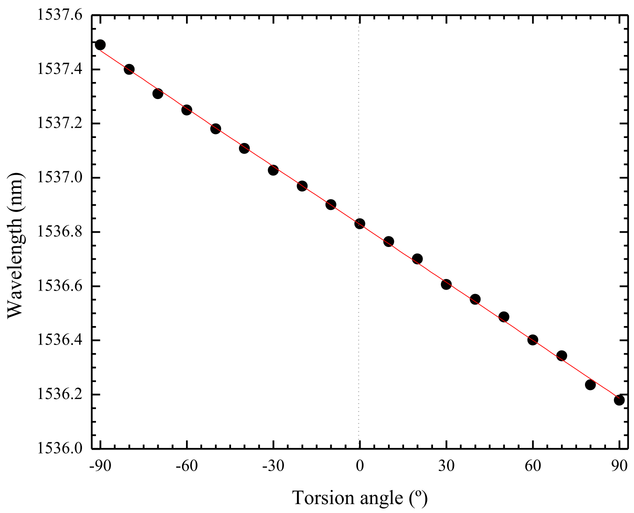

Figure 6. Wavelength variation with applied torsion.

higher wavelengths (red shift). Accordingly, by decreasing the angle from 0° to −90°, a shift towards lower wavelengths (blue shift) was observed. The applied torsion range was [−90°; 90°]. However, the behaviour is periodic, according to the filter spectrum (see figure 5).

Considering the variation of the wavelength with the applied torsion (see figure 6), there is a linear decrease in wavelength for this torsion angle range, which led to sensitivity of −7.13 pm/degree. It should be noticed that the analysis could also be applied to variations of optical power, since the laser emission varies depending where it is placed in relation to the interferometric filter. Thus, when the wavelength corresponds to a maximum at the interferometric filter spectrum, a maximum also occurs in the laser peak emission, decreasing according to the behaviour of the filter.

3. Conclusions

In summary, a torsion active sensor based on a figure-of-eight laser cavity was demonstrated. The interferometric filter was made up of a section of photonic crystal fibre which also acted as a sensing element. In order to achieve single band laser emission, a polarization controller was inserted into one of the loops. Torsion was applied over a range of 180°and both wavelength and optical power changed, the latter being due to the properties of the optical filter. A sensitivity of −7.13 pm/degree was obtained. Since the filter presents low sensitivity to temperature, in addition to its low cost, ease of fabrication and reliable results, it proves to be a good choice for performing active torsion measurements.

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