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Wavelength tunable fiber ring laser for high-speed interrogation of fiber Bragg grating sensors

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ABSTRACT

A wavelength tunable erbium-doped fiber ring laser dedicated to high-speed interrogation of Fiber Bragg Grating (FBG) sensors has been realised and characterised. A standard FBG is used as the output mirror whereas an intra cavity spectral filter formed by a π-phase-shifted FBG is implemented to narrow the output laser spectrum down to 0.5 pm. The emitting wavelength is tuned at 500 Hz over 3.6 nm by simultaneously straining both the standard and π-phase-shifted FBG with a piezoelectric actuator. An all-fiber Michelson interferometer is used to accurately determine the spectral scanning range. Bragg wavelength increments equal to 1.3 pm are resolved combining both wavelength referencing with an absorption gas cell and amplitude normalisation versus the laser output power. This instrumentation is designed to be embedded in a train cabin for making on-board strain and temperature measurements on pantographs with FBG sensors.

Keywords: tunable fiber laser, Fiber Bragg Grating, interrogation system, rolling stocks monitoring, pantograph

1. INTRODUCTION

Initiatives are developed throughout the world and specially in the European Union to enhance train transportation as alternative transportation means are gradually becoming saturated. Promoting rail grid by means of deregulation and interoperability raised new needs for on-train diagnostics of infrastructures. One key issue consists of monitoring the interfaces such as tracks to bogies [1] or pantographs to catenaries. Concerning this last purpose, operators need to measure the thermal and mechanical stress loads caused by high-speed train on overhead contact lines; such data will allow to compute the current collector wear. In this purpose, FBG sensors are promising candidates due to intrinsic advantages such as immunity to electromagnetic interference, wavelength-encoded information, multiplexing capabilities and low intrusivity. The European SMITS – Smart Monitoring In Train Systems - project aims at developing this technology by embedding FBG into carbon current collectors [2]. To meet the project requirements, a high-speed wavelength interrogation unit working at 500 Hz with a picometer resolution has been developed. A wide variety of techniques have been demonstrated for high-speed monitoring of the Bragg wavelength shift. Bragg wavelength may be measured either by interferometers, edge filters or tunable filters (such as Fabry-Perot) [3]. The main drawback of these techniques is the optical throughput power penalty. In order to optimise both signal-to-noise ratio and spectral resolution, we have developed a wavelength tunable Erbium-Doped Fiber Ring Laser (EDFRL) [4-8]. This laser incorporates a standard FBG as output mirror and a π-phase-shifted FBG as intracavity filter to improve the effective linewidth of the laser [9,10]. Wavelength tuning is achieved by simultaneously straining the two FBGs thanks to a piezoelectric actuator [11].

2. LASER CAVITY CONFIGURATION

The schematic diagram of the fiber ring laser developed in this study is presented in Fig. 1. The erbium-doped fiber section is forward pumped through a wavelength multiplexer by a 180 mW diode laser source emitting at 980 nm. The output of the erbium-doped fiber is spliced to port 1 of an optical circulator. On its port 2, a standard FBG acts as the laser cavity output mirror. Filtered light reflected back by the FBG is transmitted *via* port 3 to the π-phase-shifted grating. The laser beam comes out through the standard FBG.

Due to their long cavity length (typically 10 m), erbium-doped fiber ring lasers (EDFRL) exhibit a very narrow mode spacing (20 MHz). However, mode competition between longitudinal modes easily occurs. Mode selection can be achieved using intracavity spectral filters: hence mode hopping may still occur, but only between modes lying under the spectral envelope of the filter response. When using only a standard FBG with a bandwidth of 250 pm as wavelength-selective output mirror, we typically obtain an effective linewidth equal to 15 pm. However, current applications of FBG sensors require interrogation units achieving picometer wavelength resolution. So, to improve the effective linewidth of a FBG-based EDFRL, a second spectral filter has been incorporated inside the ring cavity [9]. This filter is formed by a π-phase-shifted FBG with the same Bragg wavelength than the standard FBG. In the middle of its stop band, such a grating exhibits

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a very narrow pass band whose bandwidth is typically equal to 15 pm. Therefore, at the output of this highly selective filter, the bandwidth of the light reflected by the standard FBG is reduced by a factor of 15. Fig. 2 shows the narrow pass band (FWHM = 15 pm) extracted using a standard FBG, as depicted on Fig. 1.
Wavelength tuning of the laser is achieved by dynamically and simultaneously straining both FBGs. Axial strain is applied to the fiber by a piezoelectric actuator and specifically designed mechanical frames. The main issue consists of keeping the two Bragg wavelengths strictly equal, at first when the two gratings are mounted on the actuator's frames, and also when they are simultaneously strained to tune the laser wavelength.
To make this task easier, the two FBGs are photowritten using a single phase mask which incorporates a phase shift in its middle: the standard FBG is realised by simply shifting the UV-writing beam to a location on the mask without the phase shift. As the two gratings may have different reflectivities (R > 95% and R ∈ [50% 90%] respectively for the phase-shifted and the standard FBG), the Bragg wavelength of the standard FBG is slightly shorter than that of the phase-shifted grating. To compensate for this difference, the fiber used to photowrite this last grating is prestrained during grating manufacturing. In this way the two gratings present almost the same period.

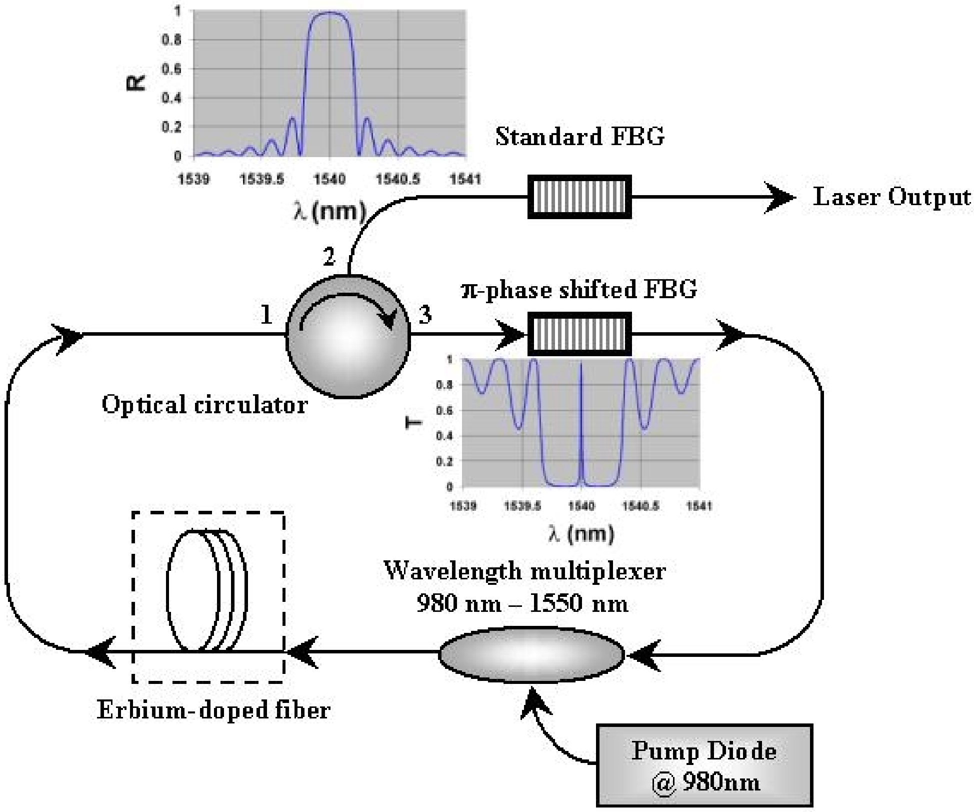

Fig. 1: Erbium-doped fiber ring laser configuration.

3. LASER OUTPUT SPECTRAL CHARACTERIZATION

The gap between the frames assembled on the piezoelectric actuator can be adjusted between 3 mm and 5 mm. Therefore the FBGs need to be shorter than 5 mm in length. A 4-mm long standard FBG has been photowritten in a singlemode and polyimide coated optical fiber using a phase mask interferometer (mask period = 1067.5 nm). The FWHM of the stop band is equal to 300 pm and its reflectivity is 80%. The π-phase-shifted FBG is also 4 mm in length (phase shift at its center) but the reflectivity exceeds 98% and the FWHM is equal to 1100 pm whereas the central pass band is 15 pm in width. Once the two FBGs are mounted on the actuator's frames, they are inserted in the ring laser cavity.
The spectral purity of this laser source has been characterised with a piezoelectrically scanned confocal Fabry-Perot interferometer. The maximum resolution is 27 MHz (equivalent to 0.2 pm at 1550 nm) for a Free Spectral Range of 8 GHz (64 pm @ 1550 nm) and a Finesse greater than 300. The scanning period is selected to be 20 ms. Using the wavelength-stable monomode output of an external cavity laser diode, the interferometer is aligned and the amplitude of the scanning ramp is adjusted to scan a single order.
In a first step, the spectral purity of the laser has been tested without the π-phase-shifted FBG: the only spectrally selective filter is the standard FBG. 32 samples are acquired with the Fabry-Perot interferometer and averaged. The FWHM of the

envelope is equal to 15 pm whereas that of the FBG is 300 pm. By incorporating the π-phase-shifted FBG in the ring cavity, the effective linewidth (32 averaged samples) is reduced to 0.5 pm which corresponds to an improvement by a factor of 30 (see Fig. 3). The laser output power is measured to be 4 mW for a 100 mW pump power. This corresponds to a power drop of 30% with respect to the case of the laser using solely the standard FBG. Moreover an optical signal-to-noise ratio better than 50 dB is measured using an Advantest Q8383 spectrum analyzer.

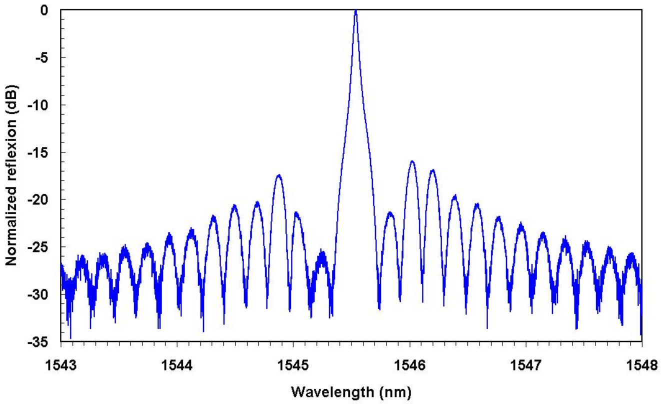

Fig. 2: Central transmission peak of a π-phase-shifted FBG extracted by a standard FBG.

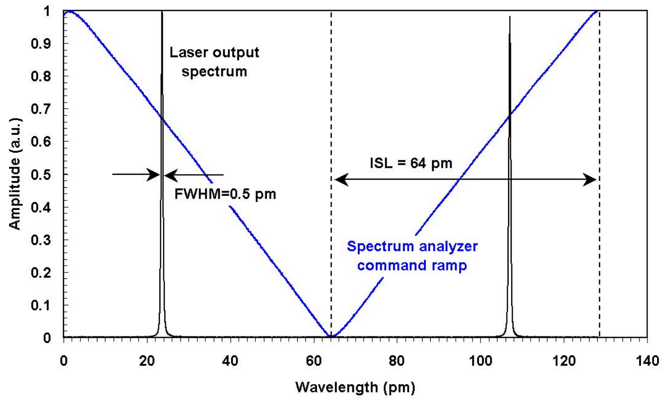

Fig. 3: Fiber ring laser output spectrum with a π-phase shifted FBG as intracavity filter.

4. DYNAMIC WAVELENGTH TUNING USING A PIEZOELECTRIC ACTUATOR

The laser wavelength tuning is achieved by axially straining the two FBGs simultaneously using a piezoelectric actuator fed by a power supply with a bandwidth of 1 kHz and delivering up to 6 A. The main issue is to characterise the spectral behaviour of the laser at the tuning speed we are interested in, that is at a driving frequency of 500 Hz over a spectral range of several nanometers.

To evaluate the spectral tuning range of the laser, we have realised an all-fiber Michelson interferometer with a 2x2 fiber coupler. End mirrors are formed by two fibers whose ends are cleaved and metallised. The path length difference is roughly equal to 1 cm. This interferometer is calibrated using an external cavity tunable laser diode (working in continuous tuning mode) together with an hydrogen cyanide absorption gas cell. Using a 2x2 coupler, the tunable source interrogates both the gas cell and the Michelson interferometer: the fringe pattern and the transmission spectrum of the cell are acquired simultaneously. By counting the number of fringes between two absorption bands of the gas cell (distant from 30 nm and whose wavelength are precisely known) we easily deduce the interfringe value to be 73.7 pm. This is equivalent to a path length difference of 1.1 cm.

Using this interferometer, we measure the spectral range scanned by our tunable fiber ring laser driven at 500 Hz at half of the maximum driving ramp amplitude. The interferogram corresponds to a tuning range of 3.6 nm.

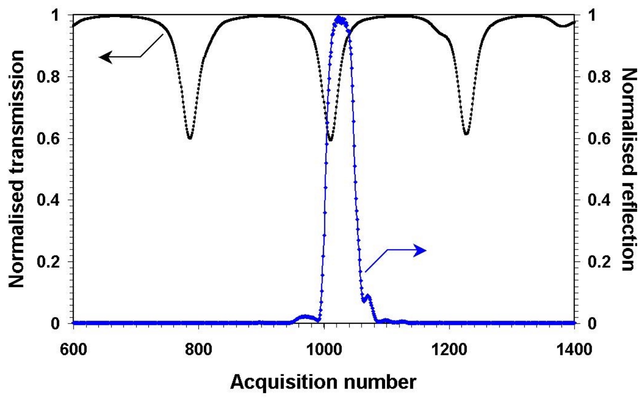

Fig. 4: Transmission spectrum of a 100 Torr $H^{13}C^{14}N$ absorption cell and reflection spectrum of a FBG measured with the tunable EDFRL laser scanning 3.6 nm at 500 Hz (data normalised with respect to the laser output power).

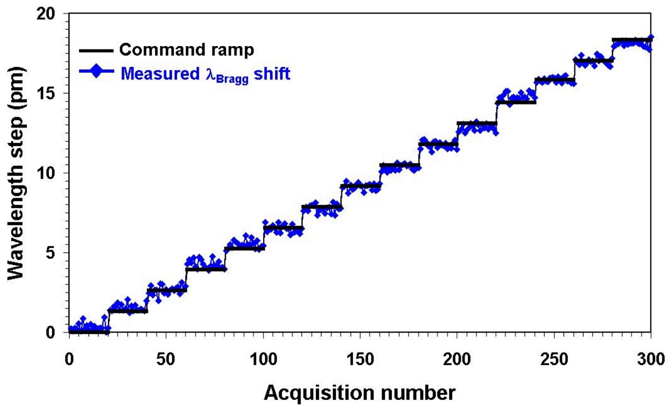

Fig. 5: Estimation of the spectral resolution of the tunable EDFRL laser measurement system by comparing the actual and measured Bragg wavelength step increment of a FBG sensor strained using a high-resolution tensile setup.

We have also estimated the achievable spectral resolution when this laser is used to interrogate FBG-based sensors. A motorised tensile setup applies strain to a standard FBG sensor interrogated by the laser. This tensile setup is 1.2 meter in length and the motorised translation stage has a resolution of 0.1 µm. We apply wavelength step increments of 1.3 pm on the FBG sensor regulated at 25°C with a Peltier element. The fiber ring laser is connected to a 3x3 optical coupler. Its first output arm is connected to the FBG sensor, the second one to the absorption gas cell whose spectrum is measured in transmission, and a photodiode (connected to the third output arm) measures the laser output power during tuning for power normalisation purposes. A 3.6 nm spectral range is scanned by the laser at 500 Hz while the three signals are acquired with a data acquisition board sampling each channel at a frequency of 1 MHz. After power normalisation and analog low pass filtering of both the FBG and gas cell signals (typical signals are given on Fig. 4), we deduce the Bragg wavelength of the sensor through identification of the two nearest absorption bands and linear interpolation of the Bragg resonance location. Fig. 5 shows the driving ramp applied by the tensile setup to the FBG sensor (14 steps of 1.3 pm each) together with the Bragg wavelength measured by the fiber ring laser (20 acquisitions/step). The measured Bragg wavelength follows quite well the increments of the ramp, which is a very promising result in the prospect of achieving picometer resolution.

5. CONCLUSION

A wavelength tunable Erbium-Doped Fiber Ring Laser of high spectral purity and high tuning speed has been proposed and realised. Matching the resonance wavelength of a FBG-based output mirror, a π-phase-shifted FBG acting as an intracavity filter has been incorporated inside the ring cavity. The effective linewidth of the laser has been reduced to 0.5 pm which corresponds to an improvement by a factor of 30 with respect to the case of a single standard FBG used as wavelength-selective mirror. Feasability of scanning over 3.6 nm at a driving frequency of 500 Hz has been proved by simultaneously straining the two FBGs with a dedicated piezoelectric actuator frame. The tuning range has been measured using an all-fiber Michelson interferometer. Bragg wavelength measurement with a resolution of 1.3 pm has been achieved on a standard FBG used as a strain sensor. The absolute wavelength measurement is provided by the use of a HCN absorption gas cell which also provides intrinsic compensation of actuator non-linearities.

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