WDM and TDM interrogation by sequentially pulsing direct modulated DFBs

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Abstract: A new versatile and cost-effective interrogation system by pulsing direct modulated (DM) DFB laser diodes is proposed. 1 pm wavelength resolution and 600 m sensor spacing is demonstrated by sequentially pulsing a DM DFB.
OCIS codes: (140.3510) Lasers, fiber; (060.2370) Fiber optics sensors; (060.2430) Fibers, single-mode

1. Introduction

Optical fiber sensors (OFS) multiplexing capability offers a competitive differentiation with regard to other sensing technologies. Characteristics such as the large number of sensors that can be multiplexed in a single network (even distributed measurements can be achieved) and the remote sensing capability are among the main distinguishing features. Nowadays, optical fiber technology is mainly centered on niche applications; that is, focusing on specific solutions that cannot be done using conventional technologies [1]. After a few decades of research, OFS are still far behind the development degree of other technologies such as electric sensors; especially in terms of cost per sensor.

In order to reduce the gap between technologies and widen the type of applications in which OFS are competitive, research and technological development is continuously done. Together with the scientific advances in OFS, the cost of optical equipment has decreased due to the expansion of fiber optics solutions for communications. Taking into consideration the mature state of the technology together with the drop in the costs, we believe that there are increasing opportunities in developing cost-effective (or even low-cost) OFS solutions. Therefore, effort is being focused on the development of new interrogation systems that are competitive enough to be used in applications formerly out of reach for OFS.

Different research groups around the world explored the wavelength-tuning feature of laser diodes when their current, temperature, pressure or magnetic field are modulated [2]–[5]. These techniques enable the possibility of developing interrogation systems that can be engineered to be used with multiple optical fiber sensing technologies [6], in dense multiplexing sensor networks [7], [8], distributed sensing [9], [10] or long-distance remote sensing [11].

In this contribution, we present the development of a simple interrogation system based on the continuous wavelength sweep due to the direct modulation of the current of a laser diode in combination with a temperature change. In this case, to increase the multiplexing capability we introduce the TDM feature by using an external modulator that sequentially chopped the chirped light after its generation. The system is validated by monitoring both fiber Bragg gratings (FBG) and interferometric sensors. This approach presents high multiplexing capability while retaining the simplicity, robust performance and the ability of being adapted to design a cost-effective solution.

2. Principle of operation

As mentioned before, to create a wavelength sweep and to introduce the ability of separating multiple sensors in the time domain, the continuous direct modulation of a LD is sequentially chopped using pulses. In order to avoid reflections overlapping, as in any time-domain reflectometry approach, the period of repetition between pulses must be greater than the time-of-flight of each pulse in the network. On the other hand, distance between sensors must be larger than the pulse width to avoid overlapping between sensors. Thus, as illustrated in fig. 1, by imposing a pulse repetition period: $P = T_r + t_p$; the spectrum can be reconstructed by sequentially concatenating the reflected pulses. The spectral resolution achieved is directly proportional to the pulse width, which also limits the spatial resolution, as in every optical time-domain reflectometry (OTDR) approach. Consequently, the shorter the pulse-width is, the higher the spectral resolution is. Inversely, shorten the pulse comprises an increment of the scanning time following this expression: $S = T_r \cdot (T_r + t_p)/t_p$

In this case, although each portion of time has continuous wavelength information, intensity contained in each reflected pulse is integrated to increment the system signal-to-noise ratio (SNR). Besides, it also relieves wavelength broadening due to, mainly, non-linear effects generated by the narrow and intense light propagating through the fiber.

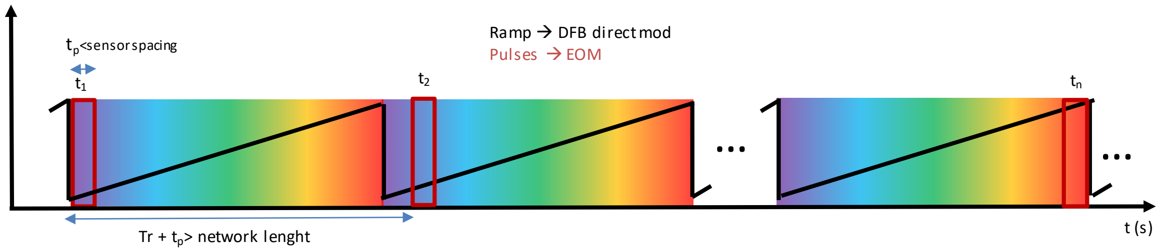

Fig. 1. Schematic depiction of the principle of operation of the WDM/TDM interrogation system.

The frequency ramp is applied to the laser diode by means of the direct current modulation using a sawtooth signal. However, Distributed feedback (DFB) laser diodes are also temperature-sensitive. Because the wavelength change due to temperature variations is higher in a safe diode operation range, extended wavelength operation can be performed by adjusting the thermoelectric cooler (TEC) controller. Therefore, high resolution spectral measurements can be done using direct current modulation and then, the process is repeated for different TEC temperatures to reconstruct a wider spectrum. To accurately do this, the laser performance must be characterized. In the case of this experiment, a 1 MHz DFB LD @1559 nm (Emcore Corp.) laser was used. It presents a wavelength shift range of 4.2 nm between 15 ºC @ 40 mA and 35 ºC @ 260 mA. A complete characterization diagram is shown in fig. 2.

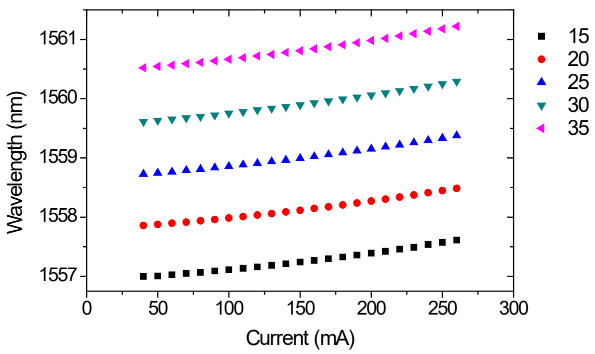

Fig. 2. Temperature and current characterization of the laser performance. Data in legend is in ºC

2. Experimental setup

The basic operation of the device was experimentally demonstrated by designing a proof-of-concept setup shown in Fig. 3. The setup is based on a tree structure formed of three fiber optic couplers placed 6 km away from the monitoring station with a 5 km gap between them. From each coupler, FBG sensors (FBG1 to FBG4), a broadband mirror and an in-fiber Fabry-Perot temperature sensor (S1) (high Q-100 GHz FSR).were placed. The separation between couplers and sensors will lead to a separation in the time/wavelength resulting diagram (Fig 5). This simple network configuration aims to show the capability of the system to interrogate different types of fiber optic sensors. In this manner, three FBGs with almost equal central wavelength, other different, a broadband reflector and a resonator with multiple peaks along the spectrum were placed inside the network. Thus, the objective of the proof of concept setup is fulfilled by validating the performance of the interrogator in a network including sensors of different nature and locations.

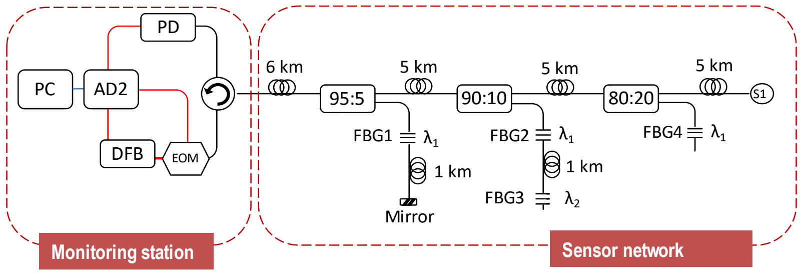

Fig. 3. Schematic setup of the proof of concept WDM/TDM sensor network interrogated by the proposed system. PC: Personal Computer, PD: Photodiode, AD2: Analog Discovery 2, DFB: Distributed Feedback laser source, EOM: Electro Optical Modulator.

The monitoring station is composed by the 1 MHz @1559 nm DFB LD mounted in a commercial laser and TEC controller (Thorlabs CLD1050). The optical source output is connected to an intensity electro-optical modulator (EOM). Hence, the circulator routes the outgoing light to the sensor network and the reflected light to a 125 MHz photodetector. A custom software controls a low-cost FPGA-based multi-function instrument: Analog Discovery 2 (AD2). This element drives all the opto-electronic devices: it generates the ramp and the sequence of pulses signals to modulate the DFB and the EOM respectively and provides DC outputs to control the bias point of the modulator. The response of the sensors is also retrieved by one of its oscilloscope channels. On the other hand, the custom software controls the TEC of the laser aimed to increase the wavelength range of the system.

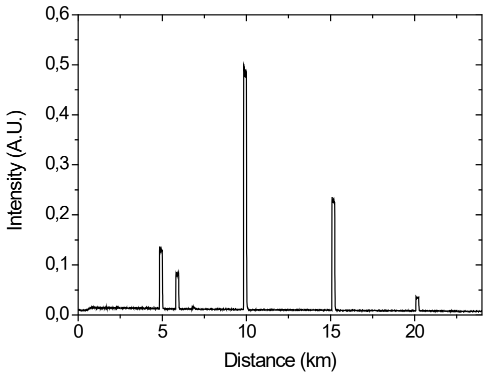

Fig. 4. Oscilloscope sample trace of the sensors interrogated with the proposed system. Note that FBG3 has no reflection at this wavelength.

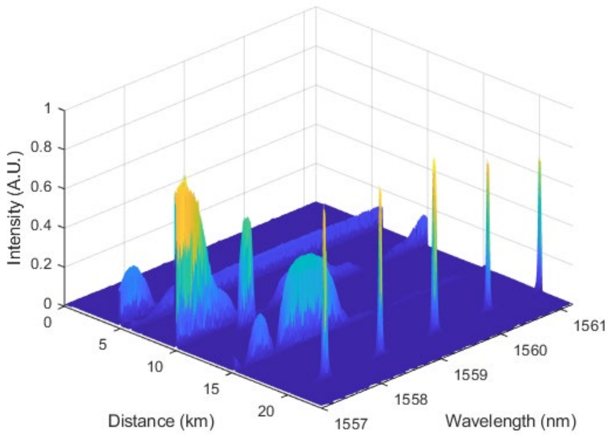

Fig. 5. 3D depiction of the wavelength and spatial distribution of the different OFSs.

Fig. 4 depicts a sample trace of the proposed setup. It represents the reflected power induced by a single pulse versus time/distance; thus, it contains the power reflected for a single wavelength. Note that FBG3 is not present in the trace, because the central wavelength of the FBG does not match with the wavelength of that pulse. .A sequence of traces are obtained for every scanned wavelength so the system can provide a high-resolution reconstruction of the spectrum of the sensors along the length of the network (Fig. 5). As aforementioned, system resolution is proportional to the pulse-width. In this case, the ramp repetition period is T_r= 1 ms and the pulse width 2 μs or a ramp wavelength excursion of 0.6 nm, giving a wavelength resolution of 1.2 pm and a scanning rate of 501 ms.

3. Results

To demonstrate the correct system operation, we have characterized FBG4 by applying axial strain and a temperature sweep was performed to the in-fiber Fabry-Perot sensor (S1). Results were obtained by executing a software routine that first performed a full wavelength range reading by tuning the full TEC temperature range. Once all the sensors were located, the sensors of interest were interrogated independently at the highest frequency rate. Both showed the expected linear response following their sensing specifications.

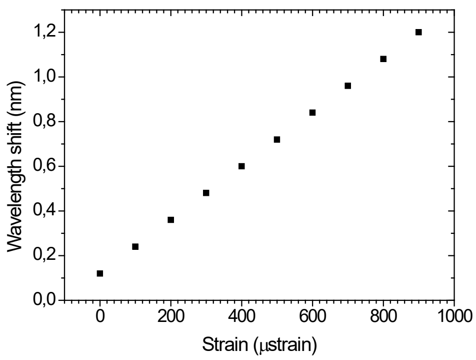

Fig. 6. Wavelength shift behavior when straining FBG4 and interrogated with the system.

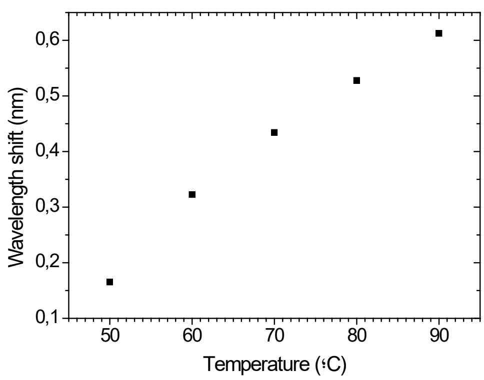

Fig. 7. Wavelength shift with temperature of S1 (FP sensor) when interrogated with the system.

4. Conclusions

In conclusion, this work presents a new cost-effective WDM/TDM interrogation system by sequentially pulsing a directly-modulated LD. A proof-of-concept sensor network was experimentally developed and tested. The network includes different sensing technologies capable of measuring different parameters. The interrogation system presents high resolution in wavelength, showing resolutions around 1 pm, using cost-effective components.

Furthermore, by controlling the LD TEC, interrogation wavelength range can be extended. Then, the combined WDM and TDM performance significantly extends the multiplexing capabilities of the proposed system. A natural evolution of the system would adapt this approach to a distributed solution, as other authors already presented [9,10]. However, the aim of this work is to explore the feasibility of creating a flexible and cost-effective OFS interrogator able to monitor any type of sensor. In fact, further work is being done in reducing the amount and required specifications of the involved equipment; for instance, by employing direct pulse-modulation in the LD.

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