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Development of a Low-Cost Interrogation System Using a MEMS Fabry-Pérot Tunable Filter

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Abstract. The interrogation of optic fiber sensors usually relies in complex and costly equipment with low portability due to their size such as Optical Spectrum Analyzers (OSA) or high-resolution spectrometers. Because of this, micro spectrometer devices, such as Micro-Electromechanical Systems (MEMS) with Fabry-Pérot tunable filters, are emerging as simpler and compact alternatives capable of being used to acquire spectral information in a wide wavelength band. In this work it is described the development of an interrogation system capable of infrared spectroscopy using a MEMS Fabry-Pérot Interferometer (MEMS-FPI) with a spectral response in the 1350nm to 1650nm range. Its performance is tested with the interrogation of long period fiber gratings both as a refractive index sensor and as a temperature sensor. Deconvolution techniques such as Wiener filtering are used to reduce the impact of the tunable filter's impulse response in the measured signal. Results are comparable to those obtained using a typical OSA which shows the system's potential as a cheaper and more transportable alternative.

Keywords: Fabry-Pérot; Interrogation Techniques; Long Period Fiber Grating; Optical Fiber Sensors.

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1. Introduction

The use of optical fiber sensors has become more and more commonplace due to several characteristics they present. Most notably, optical fiber gratings are optical sensors which have good versatility, are easy to manufacture and have a relative low-cost since they can be formed in cheap and common telecommunication fiber.

These gratings are formed by periodic modulations of the fiber's refractive index. In the case of Long Period Fiber Gratings (LPFGs) this modulation causes the core mode of the fiber to couple light to co-propagating cladding modes at wavelengths that satisfy the resonance condition [1]:

$$\lambda_{res} = (n_{eff}^{co} - n_{eff}^{cl,n})\Lambda$$

where n_{eff}^{co} is the core mode's effective refractive index, $n_{eff}^{cl,n}$ is the effective refractive index of the nth cladding mode and Λ is the grating period.

However, to interrogate these types of structures, often complex and costly equipment is needed such as commercial Optical Spectrum Analyzers (OSA), which are bulky and not suited to work outside of the laboratory [2], or specific interrogators which usually have very short spectral response ranges.

The use of microspectrometer devices such as Micro-Electromechanical Systems (MEMS) combined with Fabry-Pérot tunable filters might help solve these problems since they are compact, cheaper than their alternatives and have relatively large spectral response ranges [3].

2. Materials and Methods

2.1. MEMS-FPI

The proposed system is based around a MEMS-FPI device [4] whose structure can be seen in figure 1.

The device has a tunable FPI filter composed of two mirrors that form a Fabry-Pérot cavity. This cavity has a wavelength transmission peak that depends in the gap between the mirrors. By applying a voltage to the two mirrors an electrostatic force is formed that adjusts the gap and allows control over the wavelength transmission peak [3,4].

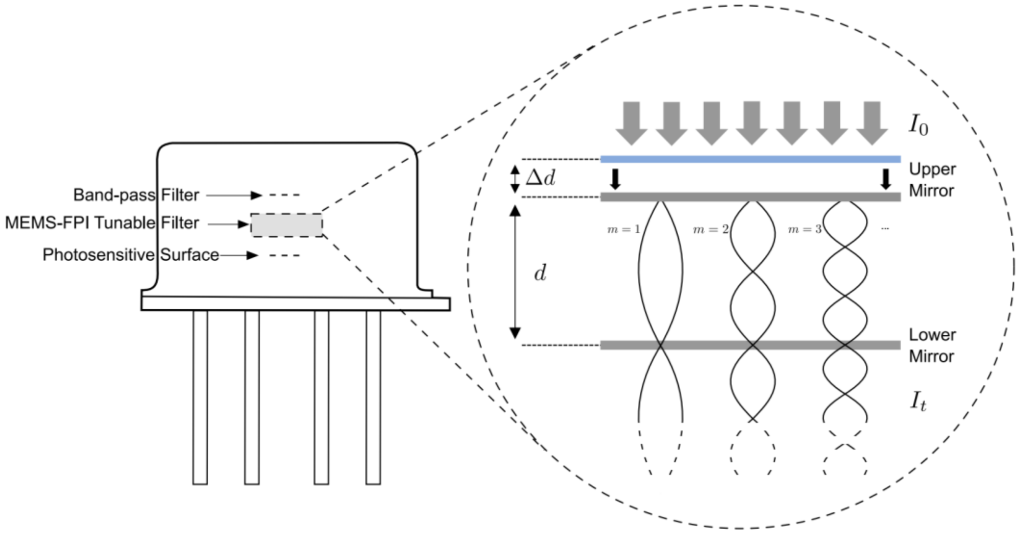

Figure 1: Structure of the MEM-FPI. It is composed of a band-pass filter, a tunable FPI filter and a photosensitive surface (Image adapted from M. Ebermann, et al [3] and datasheet [4]).

The relation between the gap and the transmission wavelength is given by the expression [4]:

$$d = m\frac{\lambda}{2}$$

where d is the gap between the mirrors, λ is the peak transmission wavelength and m is an integer.

2.2. System Overview

A dedicated electronic board was developed to control the MEM-FPI [4] delivering high precision voltages to the FP mirrors which allows it to work at different wavelengths and to amplify the photodetector signal. This board is connected to a microcontroller which establishes communication with a computer or raspberry pi where a graphical user interface was designed in python. The user interface allows the control of measurement range, time between acquisitions, number of points and visualization of the results. Figure 2 shows the block diagram of the system set up.

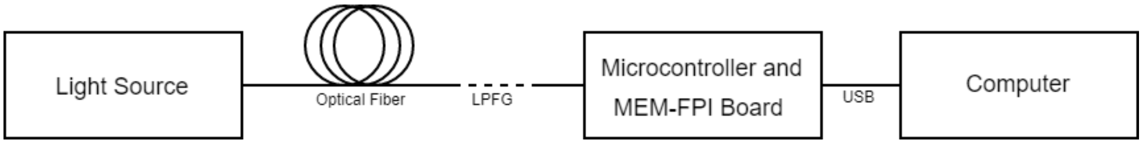

Figure 2: Block diagram of the measurement setup with an LPFG

2.3. System Characteristics

The detection system has a response range of 1350nm to 1650nm. The curve of the voltage applied to the mirrors as a function of the wavelength transmission peak can be obtained by the individual constants provided with the MEMS-FPI device which is represented in figure 3. The voltage at the filter is regulated by a voltage control circuit, which consists of two amplifiers in series. This circuit amplifies the microcontroller's DAC range of 0 to 3.3V to a range from 10.7 to 26V. The DAC's resolution allows for steps of 3.7mV at the output of the circuit.

The system has eight gain channels available which allow measurements up to 5mW. The gain is selected automatically by the microcontroller using a multiplexer. To make sure the voltage is stabilized in the correct value the system takes 10ms per point. This means that a spectrum sweep takes anywhere from 2s to 30s depending on the range and the number of points.

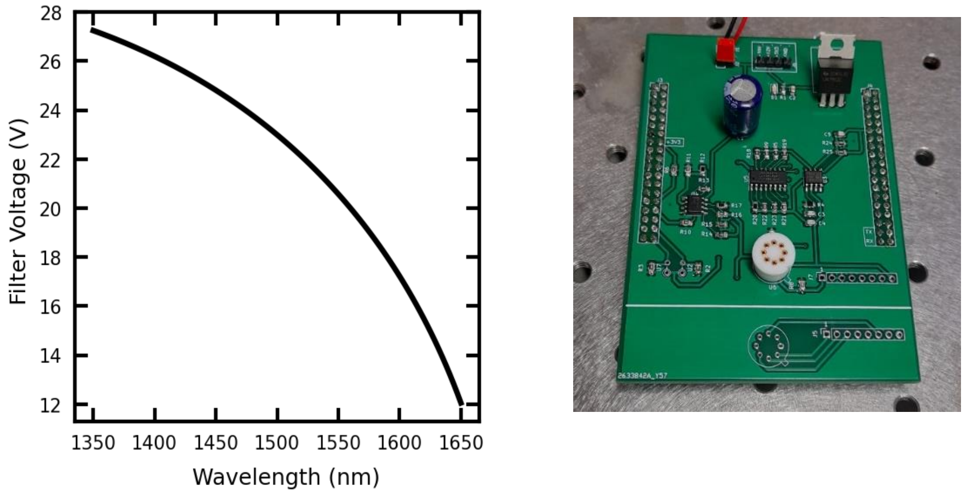

Figure 3: In the left the curve of voltage to peak transmission wavelength is represented. On the right is an image of the printed circuit board designed to control the MEM-FPI. This board is connected to a STM32 microcontroller board [5] for the acquisition of measurements.

2.4. Wiener Deconvolution

When taking a measurement the signal acquired by the MEM-FPI is the result of the convolution of the real signal with the impulse response of the device, such that [6]:

$$y(t) = x(t) * h(t) + n(t)$$

where *y(t)* is the acquired signal, *x(t)* is the real signal, *h(t)* is the system's impulse response and *n(t)* is the noise.

To get a better approximation of the real signal deconvolution methods can be used. The impulse response of the system's Fourier transform usually tends to zero at higher frequencies. Because of this a Wiener Filter is used to perform the deconvolution [6]:

$$X(\omega) = \frac{Y(\omega)H^*(\omega)}{|H(\omega)|^2 + Q^2}$$

Where Q is a parameter known as the noise desensitizing factor.

For the purposes of this deconvolution the system's impulse response, *h(t)*, was estimated experimentally. To do so, the MEMS-FPI filter was fixed transmitting at a certain wavelength and a tunable laser was used to sweep the filter spectrally at a rate of 0.10nm/s. Assuming that the laser is an impulse, the resulting curve is an estimation of the impulse response of the filter at that wavelength and it can be approximated by a Gaussian or Lorentzian curve.

3. Experimental Results

3.1. Deconvolution Results
Deconvolution was used to get an estimate of the real spectrum of a light source in the C and L bands and the spectrum of an LPFG. The same signal was acquired in an OSA for comparison and the results are shown in figure 4.

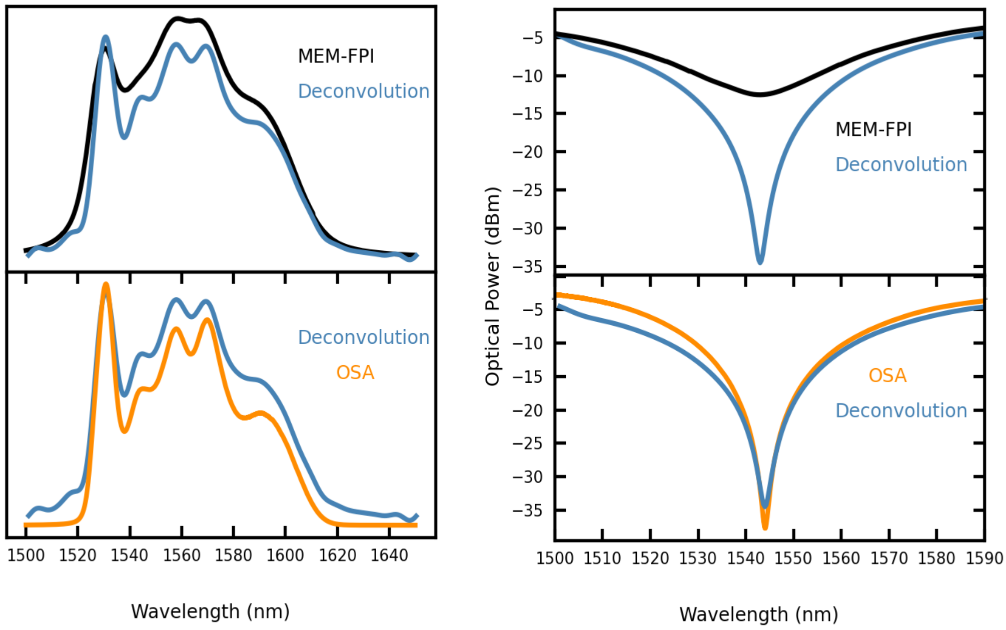

Figure 4: On the left the results of the deconvolution of the signal of a light source in the C and L bands and on the right the deconvolution of the spectrum of an LPFG. On the top is the comparison of the signal before and after deconvolution. On the bottom the comparison between the deconvolution and the measurement in an OSA.

It can be seen that the spectrum obtained by deconvolution presents sharper peaks and is a closer representation of the real signal.

3.2. Temperature Sensitivity Results
The system was used to measure the sensitivity of an LPFG to temperature. The LPFG was submitted to temperatures ranging from 150ºC to 400ºC. The temperature increase causes the spectrum to red shift as can be seen in figure 5. This shift is measured as a function of temperature and the sensitivity can be obtained by taking the slope of the curve.

The slope of the curve measured by the MEM-FPI presents 5.11% error relative to the slope of the curve measured by the OSA.

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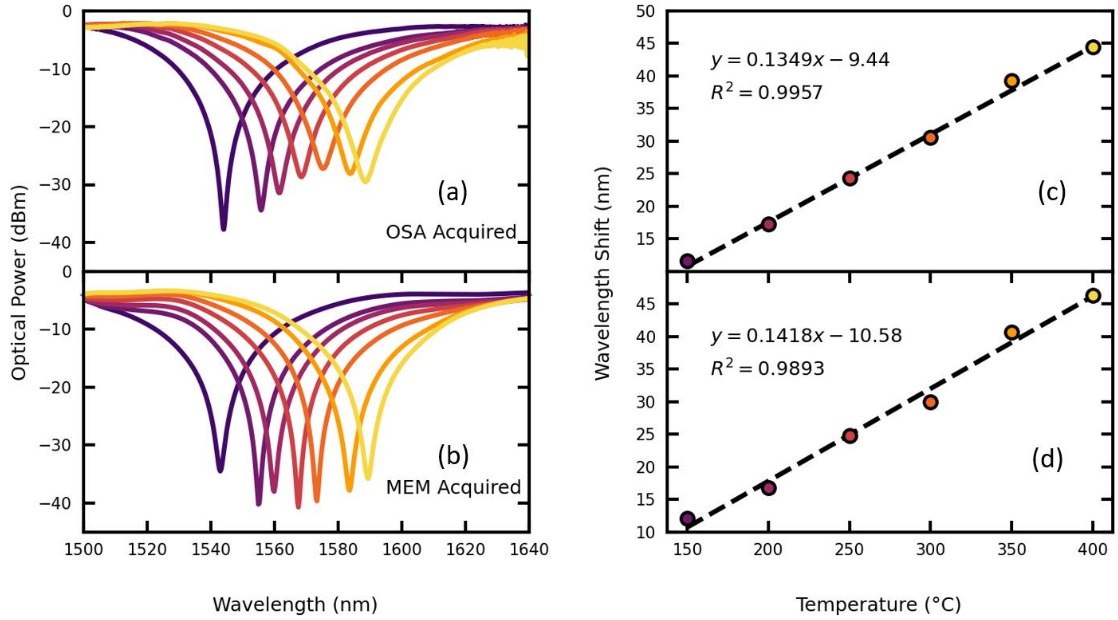

Figure 5: Experimental results of the LPFG for different temperatures: (a) spectra acquired with the OSA (b) spectra acquired with the MEM-FPI (c) LPFG calculated sensitivity using the OSA (d) LPFG calculated sensitivity using the MEM-FPI.

3.3. *Refractive Index Sensitivity Results*

The refractive index sensitivity was measured by submitting the LPFG to liquid solutions of different refractive indexes. The change in the effective refractive index of the modes causes the LPFG spectrum to blue shift as the refractive index of the environment around the fiber increases.

The results can be seen in figure 6.

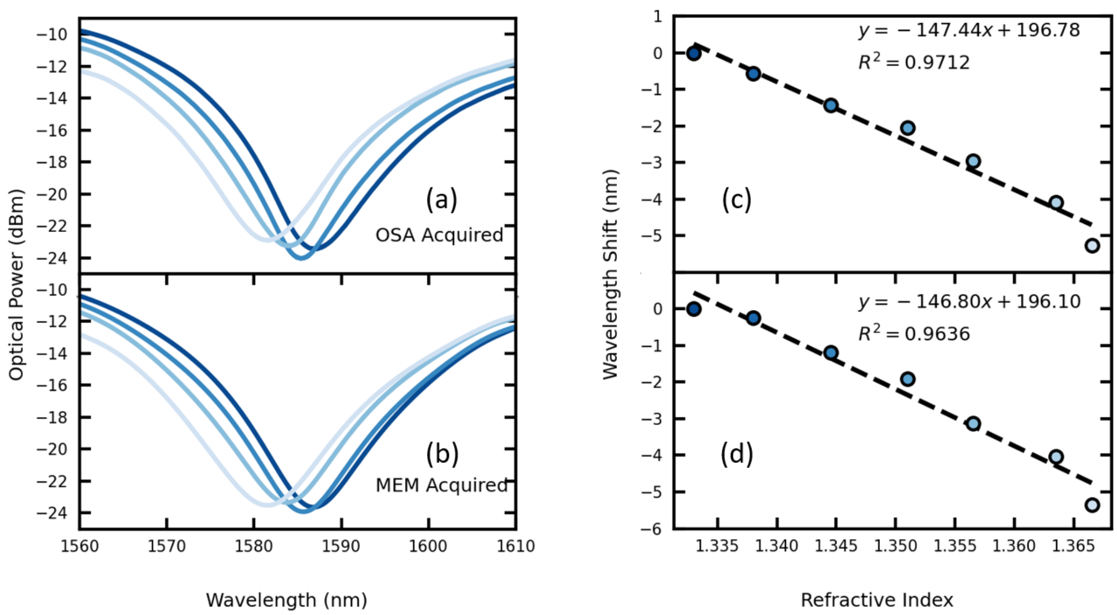

Figure 6: Experimental results of the LPFG for different refractive indexes: (a) spectra acquired with the OSA (b) spectra acquired with the MEM-FPI (c) LPFG calculated sensitivity using the OSA (d) LPFG calculated sensitivity using the MEM-FPI.

In this case the slope of the curve measured by the MEM-FPI presents a 0.43% error relative to the slope measured by the OSA.

4. Conclusion

A system capable of infra-red spectroscopy was presented as a possible alternative to commercial optical spectrum analyzers. Its performance was tested by measurements of the sensitivity of long period fiber gratings to both temperature and refractive index changes. In both cases the results were comparable to those obtained with the OSA which shows the systems potential as a much cheaper, portable alternative.

Furthermore, wiener deconvolution was used to estimate the real spectrum of the measured signal, minimizing the influence of the system's impulse response. The obtained spectrums show sharper peaks and signals closer to the ones measured by the OSA.

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