Interrogation of interferometric sensors with a tilted fiber Bragg grating

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ABSTRACT

A novel method for interrogating interferometric sensors, based on analyzing the characteristics of the light expelled from a tilted fiber Bragg grating and captured by a photodetector linear array, is presented in the paper. Also a novel algorithm for the recovery of the measured information is proposed and its performance explored. It belongs to the parametric frequency estimation methods and is an adaptation of the MUltiple SIgnal Classification (MUSIC) algorithm. Finally an insight to the possibility of interrogating multiplexed interferometric sensors is given.

Keywords: Interferometric sensors, Tilted Fiber Bragg Gratings, MUSIC.

1. INTRODUCTION

Photonic sensing is becoming increasingly popular and its applications are spreading to more and more areas [1]. This means that new problems have to be faced and new solutions have to be provided. But as the difficulty of the problems increases, so does the complexity of the proposed solutions. Therefore, in the near future it is very likely that solutions will be given in which not only one kind of photonic sensor but several ones are used. This implies that, at the present development in the sensor interrogation technology, the measured information coming from the different sensors will have to be recovered with a bench of several interrogation units. Nevertheless, this is not a good panorama in terms of economy and performance. The best solution comes from the developing of interrogation units able to extract information out of different types of photonics sensors, that is, from the developing of multisensor interrogation units. The two photonic sensors that are most likely to cohabitate, at least in the civil engineering area, are those based on Fiber Bragg Gratings (FBG) [2], and interferometers. This is not only due to their versatility but also for the fact that, together, they are able to measure most of the key mechanical parameters that are monitored nowadays. Thus FBGs are typically used to measure elongation and/or temperature; meanwhile interferometers have been widely used as elements to measure vibration [3], acceleration [4], or acoustic pressure among others.

Up to now, very little research effort has been devoted to the developing of multisensor interrogation units. Recently the authors have presented a novel FBG interrogation scheme based on analyzing the characteristics of the near-field radiation of a tilted fiber Bragg grating [5] with a photodetector linear array. In this paper this interrogation technique is adapted for allowing the interrogation of interferometric sensors. The adaptation concerns exclusively the processing algorithm and not the hardware part. In this context a novel algorithm for calculating the optical path imbalance of the interferometers is also explored. This algorithm, based on the parametric frequency estimation MUSIC one [6], performs slightly better than the classical and widely used FFT. Therefore, it can be said that the technique presented herein is a real multisensor interrogation scheme since it can recover information from both FBG and interferometer based sensors.

The paper is organized as follows: in the first section there is a brief description of the interrogation unit itself and a concise insight into the processing algorithm. The next section presents some experimental results that help to test the real performance of the unit. Between these experimental measurements a successful attempt to multiplex two interferometric sensors is also reported. At the end several conclusions are extracted.

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2. INTERROGATION SCHEME

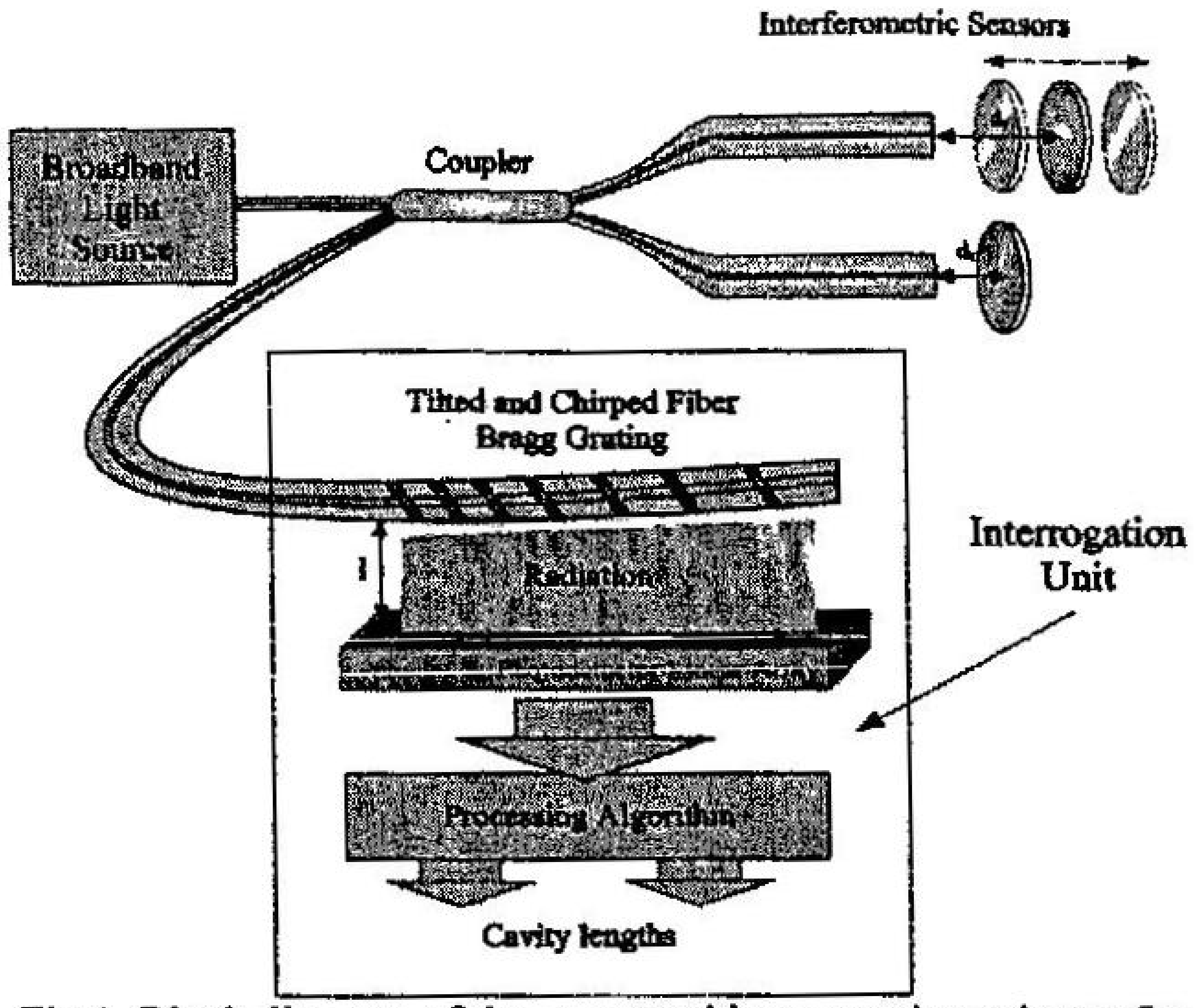

Fig.1. Block diagram of the proposed interrogation scheme for interrogating interferometric sensors.

Fig.1 shows a schematic view of the interrogation system proposed. As can be seen, and has been said before, it is formed by a tilted and chirped FBG placed parallel to a photodetector linear array at a distance l of few millimeters. The fact that the grating is chirped is because there is a great improvement of the system's wavelength resolution. It is widely known that the tilted gratings are able to extract some of the guided light to the outer medium. Therefore, having the system arranged in this way, an image, created by the radiation expelled from the fiber, will be formed at the linear array. Since the characteristics of the radiation depend upon the wavelength of the light reaching the tilted grating, the radiation images will vary with this parameter. Thus, analyzing the characteristics of the image, namely shape and position, the wavelength of the light, can be recovered. Nevertheless this simplistic approach to the operating principle is no longer valid when working with broadband light such as that coming from interferometric sensors. The problem comes from the fact that the radiation images formed at the detector array are so wide that those corresponding to the "individual" wavelengths (understanding for such discreet wavelengths that represent a range in which the characteristics of the system don't change in a substantial way) of a non-monochromatic (or broadband) light will overlap composing a more complex image. Therefore, in order to recover the "individual" contributions of these representative wavelengths a pattern recognition algorithm is required. Particularly it has been implemented by means of an adaptative filter which is a variation of the Kalman filter. Thanks to that, a certain representation of the interferometer's spectrum can be obtained. No further discussion will be included here to the basic operating principle of the technique since it has already been thoroughly presented elsewhere [7].

From the spectrum obtained after the adaptative filtering there is still another processing left to be done in order to obtain the measured parameter. This is cavity length (d) in case the sensors were based on Low Finesse Fabry-Perot Cavities (LFFPC) or, for example, optical path imbalance in case the sensors were Michelson interferometers. From now on the discussion will be centered on the LFFPC because these are the kind of sensors used to experimentally demonstrate the operating principle. However, this means no lack of generality since these devices have exactly the same sinusoidal spectrum as the rest of interferometers. So, in order to recover the cavity length from the sinusoidal spectrum of the LFFPC a frequency estimation process is required. This can be done by means of the FFT algorithm (which is the common practice) or by means of other algorithms specifically designed to accomplish this task. In particular, in the works reported herein, a parametric frequency estimation algorithm known as MUSIC has been explored. It is better suited than FFT for obtaining the frequencies of multiple sinusoids in noise since it has a much higher resolution. The problem is that this algorithm is very sensitive to the purity of the sinusoid. This means that it won't work very well with interferometric spectra since they are chirped sines. Therefore, the algorithm must be adapted for this kind of signals.

The original MUSIC exploits the fact that pure sinusoids of different frequencies are orthogonal. This means that the autocorrelation of signals composed by the superposition of pure sinusoids in noise will comprise the sum of the autocorrelation terms of the sines plus and incorrelated term due to noise, but no cross-correlation terms will appear. The latter implies that the autocorrelation matrix will have one eigenvector per sinusoid plus several more of noise (this number depends on the matrix dimension). Moreover, provided the SNR for each sinusoid is positive, the signal eigenvectors will be those corresponding with the higher eigenvalues. Knowing that all the eigenvectors of a matrix are orthogonal, then if the signal eigenvectors are multiplied by those of the noise the result will be zero. Besides, these zeroes will be located exactly at the frequencies of the different sinusoids. Thus, simply by scanning the frequencies and by looking for the zeroes of those products, the periods of the sines can be known. Nevertheless, when trying to adapt this algorithm to the chirped sinusoidal case, several problems arise. The first one is due to the non-orthogonality of these sinusoids since their frequency vary with time. This fact imposes the first limitation to the adaptation: it can only determine the cavity length of simple spectra (those coming from single cavities) not of multiplexed ones. On the other hand, there is another limiting factor in the adaptation: in the autocorrelation function of chirped sinusoids appear cross-correlation terms. These, in order to make the new algorithm properly work, must be overlooked. This omission carries with it an error that is always below the 6%, but, nevertheless, it means that the adapted algorithm is approximate and not exact. In spite of this approximation, the new algorithm performs slightly better than the FFT as will be shown in the next section.

3. EXPERIMENTAL DEMONSTRATION

A setup like the one shown in Fig.1 was used for the experimental demonstration of the proposed interrogation system. The broadband light source was a superluminiscent diode (SLD-1300 from Fiberon Inc.) meanwhile the photodetector linear array was a 512-element, 1.28 cm long, InGaAs one (Hamamatsu G8161-512S). The tilted and chirped Bragg grating was 1cm long, had a 34° tilt angle and its period ranged from 0.525 μm to 0.559 μm. With these characteristics the grating was able to efficiently outcouple light from 1250nm to 1350nm. As has been previously said, the interferometric sensors were LFFPC formed by placing the tip of a fiber right in front of a mirror attached to a motorized translation stage.

Several experiments were carried out with this setup. The first one tested the linearity of the system. In order to do so the cavity length (d_1) was swept from 90 μm to 218 μm, and the measured length was compared with the actual one. The photodetector linear array was configured to have 5ms integration time and to use a 16 bits A/D converter. The result of such experiment can be seen in Fig.2.

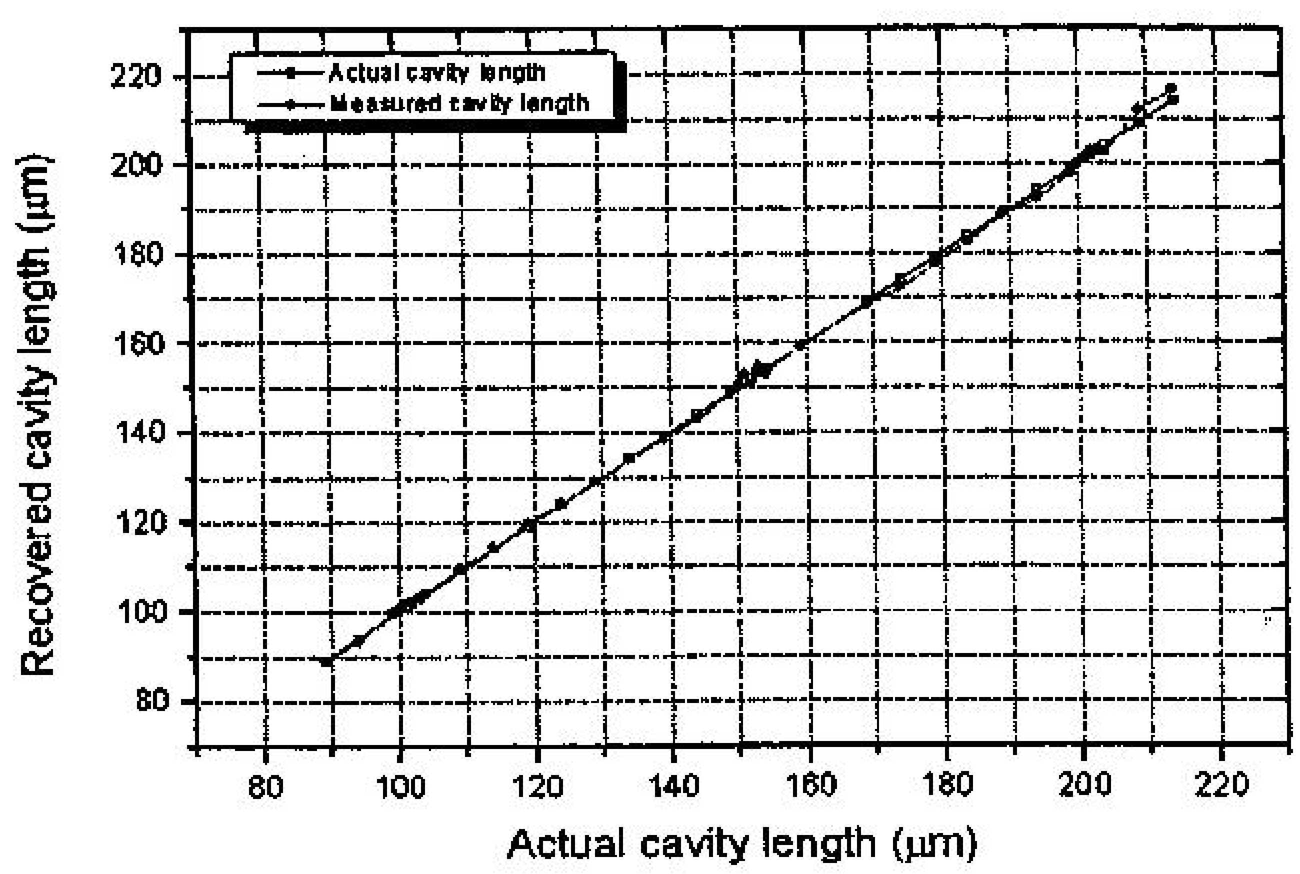

Fig.2. Results of the linearity experiment (dotted line) in comparison with the actual cavity length (squared line)

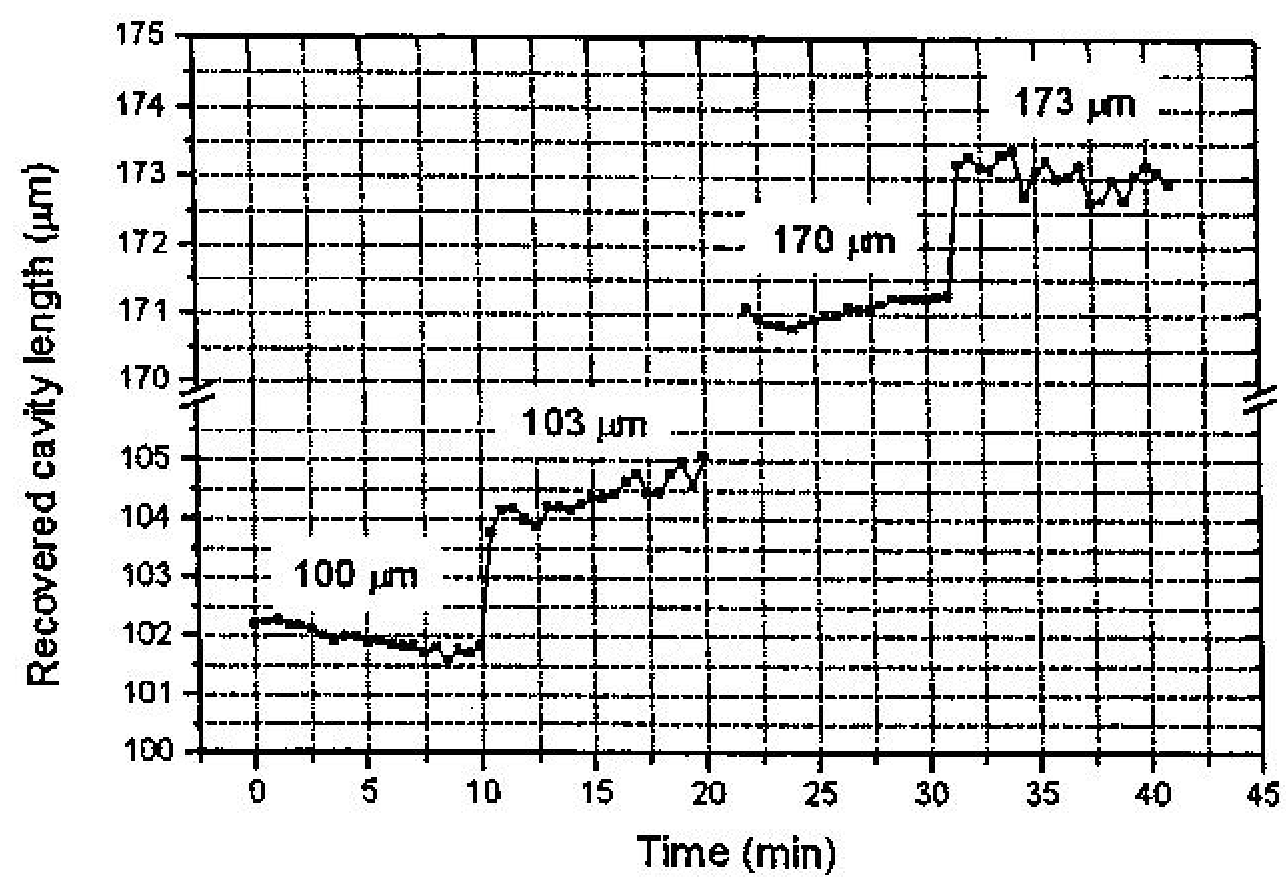

Fig.3. Results of the stability experiment when the cavity length is varied in 3μm jumps in two different areas.

As Fig.2 clearly shows, the linearity of the results is good and so is the accuracy of the recovered length. The latter is true in the range of lengths shown in the figure, because outside it the performance of the system drops considerably. The reason for that is to be found in the spectra of the cavity; beyond the lower limit, the period of the spectrum is wider than the light source, and in cavity lengths longer than the upper limit the spectrum varies too fast for the poor resolution of the interrogation unit as spectrometer. This same experiment was processed with both the adapted MUSIC and FFT algorithm, and it was found that the first one performed slightly better than the other. Thus, the average accuracy error when using the new algorithm is around 1.6 μm whereas with the FFT this value increases up to 1.85 μm. However, in both cases the accuracy of the system is around 1% of the measured cavity length. When comparing the linearity of the system, it was also found a slightly better behavior with the adapted MUSIC algorithm.

Fig.3 shows the result of the stability experiment. During it, the cavity length of the sensor was left constant for 10 minutes after which a 3 μm jump was applied. This process was repeated twice in two different starting cavity lengths: 100 μm and 170 μm. The results of this experiment show that the resolution of the system is well below 3 μm and, in fact, preliminary studies point out that this parameter can be around 0.5 μm and even less. The temporal stability of the graphs shown in Fig.3 is not very good, but the limiting factor is not the system itself but the cavity used as sensor. These devices are quite unstable and this factor turned out to be bigger than that of the system.

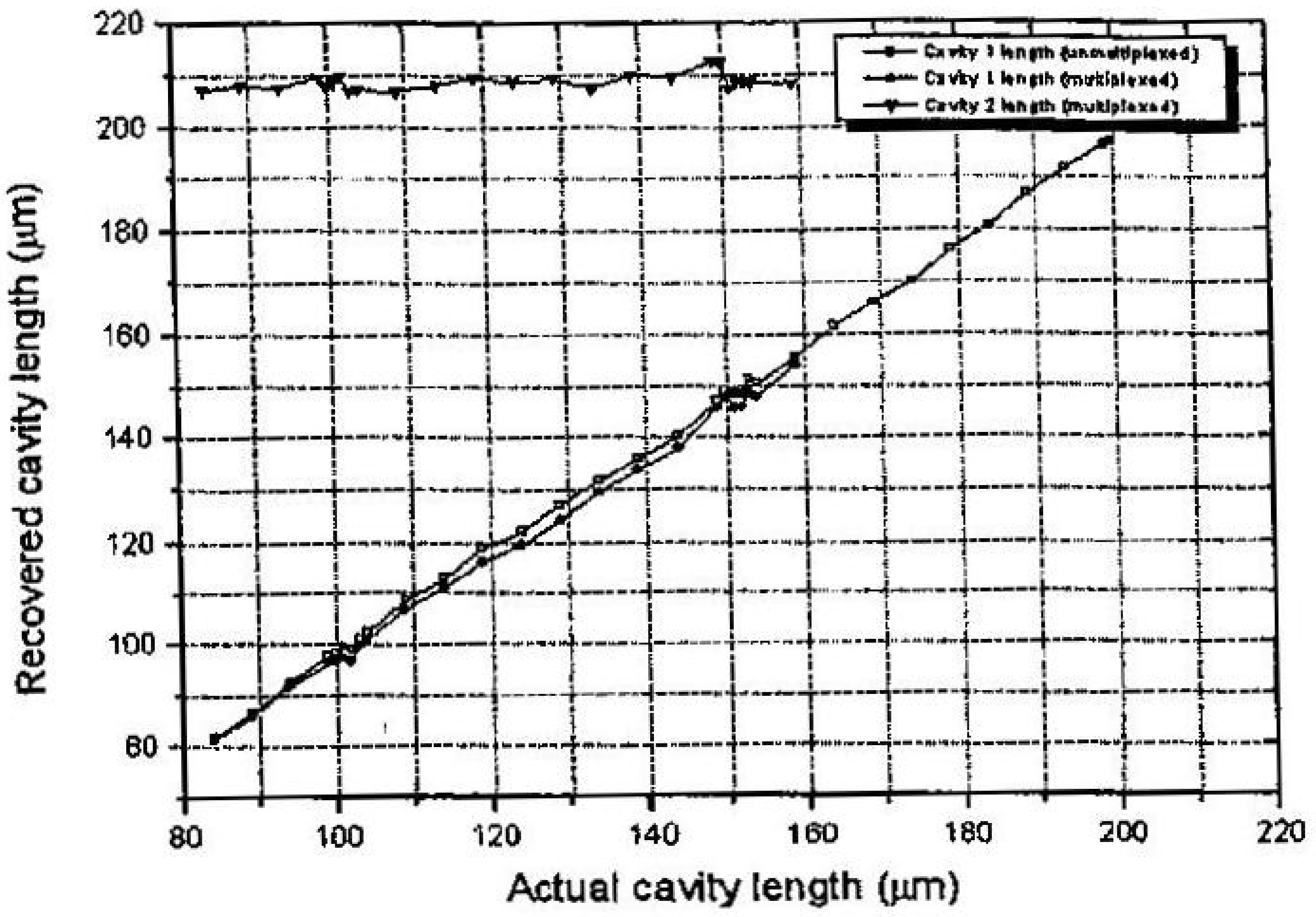

Fig.4. Graph showing the recovered lengths of two multiplexed LFFPC (dotted line and line with triangles). The result of this same sweep for a single LFFPC is also shown.

Finally there was also a preliminary attempt to recover the cavity lengths from two multiplexed LFFPC. They were multiplexed as shown in Fig.1, that is, by means of coupler. In order to achieve this goal, certain modifications were carried out in the processing algorithm. Namely, the demultiplexing part is performed by an FFT based algorithm whereas the cavity length measurement is done by the same adapted MUSIC algorithm explained above. The demultiplexing is achieved by bandpass filtering the frequency spectrum of the recovered multiplexed cavity spectrum. This implies that the lengths of both cavities should differ by a highly enough amount. A good average value for that separation is 80 µm, although in some cases, depending on the noise level (like the one shown in Fig.4), it can be significantly lower. Thus, the experiment whose results are shown in Fig.4, consisted on sweeping the cavity length of one of the multiplexed cavities from 85 µm to 200 µm, meanwhile the other cavity remained with a constant 209 µm length. It can be seen in the graph that the amount of crosstalk introduced is very low (less than 1% of the measured cavity length). This parameter can be calculated either from the ripple of the unperturbed cavity (line with triangles) or from the comparison between the recovered length of the sensing cavity when it was (dotted line) and wasn't (hollow square line) multiplexed. Also from the comparison of these two lines, it can be seen that not only the accuracy of the system but also the linearity is not affected in a substantial way. The only drawback of the technique is that the dynamic range is reduced since, in order to obtain good results, the two cavity lengths cannot differ less than 60 µm one from another.

4. CONCLUSIONS

A novel interrogation technique for interferometric sensors has been presented. This work constitutes an extension of the applicability of an interrogation device originally conceived for FBG. Therefore, it can be said that the authors present a real multisensor interrogation scheme that has a good performance in interrogating either FBGs or interferometric sensors. As a part of this work a novel algorithm for the recovering of sensing LFFPC lengths has been described and compared with the FFT. Also some insight has been given to the demultiplexing capabilities of the technique when working with interferometric sensors.

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