

Document downloaded from:

<http://hdl.handle.net/10251/102942>

This paper must be cited as:

Hervás-Peralta, J.; Tosi, D.; García-Miquel, H.; Barrera Vilar, D.; Fernandez-Pousa, CR.; Sales Maicas, S. (2017). KLT Based Interrogation Technique for FBG Multiplexed Sensor Tracking. *Journal of Lightwave Technology*. 35(16):3387-3392.
doi:10.1109/JLT.2016.2613131



The final publication is available at

<https://ieeexplore.ieee.org/document/7575720/>

Copyright Institute of Electrical and Electronics Engineers

Additional Information

KLT based interrogation technique for FBG multiplexed sensor tracking

Javier Hervás, Daniele Tosi, Héctor García-Miquel, David Barrera, Carlos R. Fernández-Pousa and Salvador Sales

Abstract—The Karhunen-Loeve transform (KLT) is used to retrieve the wavelength information of several fiber Bragg gratings (FBGs) that are acting as a multiplexed sensor. The modulated light of a broadband source is launched to the FBG cascade in order to capture the electrical frequency response of the system. Thanks to a dispersive media, the wavelengths of the FBGs are mapped in radiofrequency (RF) delays. Wavelength changes are determined by the amplitude change of the samples in the impulse response, a change which is followed by the eigenvalue calculated by the KLT routine. The use of the KLT routine reduces by three orders of magnitude the amount of points needed to have a sub-degree resolution in temperature sensing, while keeping the accuracy almost intact.

Index Terms— Optical fiber sensors, fiber Bragg gratings, microwave photonics, Karhunen-Loeve transform.

I. INTRODUCTION

OPTICAL fiber sensors not only attract attention by their inherent low losses, light weight or electromagnetic interference immunity of the optical fiber [1,2], but above all by their possibility to perform distributed and multiplexed sensing [3,4]. In multiplexed sensing an amount of discrete sensors are cascaded along a single fiber in order to measure environmental or structural parameters at certain given spots. There are several techniques to retrieve the sensor information, among which stand out the optical time (OTDR) [5] and frequency (OFDR) [6] domain reflectometry and those

Manuscript received xxxxxxxx x, 2014; revised xxxxxxxx x, 2014; accepted xxxxxxxx x, 2014. Date of publication xxxxxxxx x, 2014; date of current version xxxxxxxx x, 2014. This work was supported in part by the Spanish MINECO through projects TEC2014-60378, and by the Government of Valencia through the Research Excellency Award Program GVA PROMETEO 2013/012. J. Hervás work is supported by the MECED FPU scholarship (FPU13/04675)

J. Hervás, H. García-Miquel, D. Barrera and S. Sales are with the iTEAM Research Institute, Universitat Politècnica de Valencia, Valencia 46022, Spain (e-mail: jaherpe2@teleco.upv.es; hgmiquel@eln.upv.es; dabarvi@iteam.upv.es; ssales@com.upv.es).

C. R. Fernández-Pousa is with the Departamento de Ingeniería de Comunicaciones, Universidad Miguel Hernández, Elche 03202, Spain (e-mail: c.pousa@umh.es).

D. Tosi is with Nazarbayev University, School of Engineering, 53 Kabanbay Batyr, 010000 Astana, Kazakhstan (e-mail: daniele.tosi@nu.edu.kz).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>

Digital Object Identifier xxxxxxxxxxxxxxxxxxxxxxx

based on Microwave Photonics filtering techniques [3].

Fiber Bragg gratings (FBGs) are good candidates for the role of discrete sensors due to their mature fabrication process and the ability to record environmental parameters into their Bragg wavelength. Long, standard [7] and weak FBGs [4] have been used to measure hot spots information. Cascaded weak FBGs sensors [3] have been presented as well in order to avoid the difficult fabrication process of long weak FBGs while keeping the measurement ability almost intact. In addition, signal processing tools are being used in order to enhance sensor interrogation speed, accuracy or easiness [8, 9]. Interferometry between chirped FBGs [10] has been used to generate radio-frequency (RF) signals whose frequency is strain dependent, but its multiplexing is more complex and as is based in coherent techniques is not appropriate for certain applications. Shifted gaussian shaped filtering of ultrashort FBGs [11] has shown as well a really good performance with several advantages, like power fluctuations compensation, but this technique has a limited wavelength bandwidth with a linear response if a good sensitivity is desired.

Recently, it has been shown [9, 10, 12] that the incorporation of a dispersive element into an interrogation system provides the ability to record not only the position of a reflector but also its wavelength shift, by mapping the wavelength variations into the radio-frequency or group delay experienced by a modulated or a pulsed optical wave. In [9], we extracted this information by a similar technique to that of incoherent OFDR, namely, by computing the system's impulse response as the inverse Fourier Transform (IFT) of the frequency response.

In that work [9] we showed that the so called zero-padding technique, which consists basically in filling the raw electrical frequency data with zeros before IFT, can improve the accuracy of this wavelength to RF delay mapping. The main drawback of this approximation is the big amount of data that has to be processed in order to retrieve the overall sensor information. On the other hand, Tosi [8] has shown that the use of the Karhunen-Loeve transform (KLT) can be used to retrieve the sensing information of several optical sensors from the optical spectrum despite the coarse sampling of the optical trace.

In the present work we propose the use of the KLT in order to demodulate a WDM FBG array for temperature sensing. The system is interrogated by use of the concept of

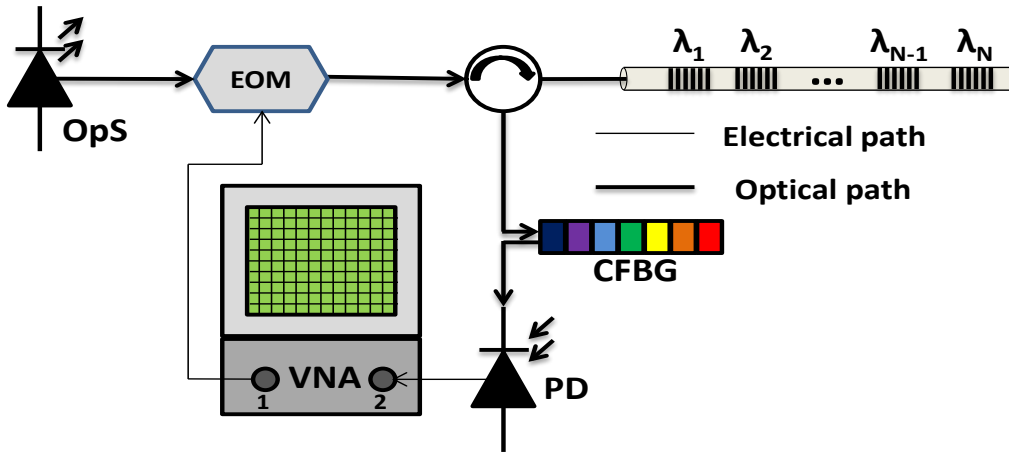


Fig.1. Schematic view of the setup used to measure the electrical frequency response. (OpS: optical source, EOM: electro-optic modulator, CFBG: chirped FBG, PD: photodetector, VNA: vector network analyzer)

wavelength to RF delay mapping, as in [9], and the KLT is used to increase the resolution of the Bragg wavelength determination from the RF impulse response without the use of the computationally costly zero-padding procedure. This approach reduces by three orders of magnitude the number of points needed to reach sub-degree accuracy in temperature sensing as compared to our previous work [9].

II. OPERATION PRINCIPLE

The operational principle is based on the use of the KLT routine to retrieve the sensor information (wavelength change) that is depicted in the impulse response trace as an amplitude change. The KLT routine records the wavelength change in the eigenvalue calculated by the routine, allowing the correct interrogation of the multiplexed sensor with a sub-degree resolution despite the coarse discretization of the temporal trace.

In order to show analytically the operational principle of this work a simulation set is going to be performed. The simulated ideal setup is depicted in Fig.1.

The setup is based on the determination of the electrical frequency response $H(\Omega)$ or scattering S_{21} parameter of the microwave photonics (MWP) filter formed by the WDM FBG array, by comparing the incoming electrical current at port 2 of the vector network analyzer (VNA) to the outgoing electrical current that modulates the broadband light at the electro-optic modulator (EOM)-

The outgoing light coming from a C&L band broadband source is modulated by the incoming RF signals produced by the VNA at the EOM. This modulated light is routed to the FBGs in the array, which slice and reflect part of this broadband source. The reflected slices suffer dispersion at a dispersive medium, here implemented with a chirped FBG, before being photodetected. This dispersive delay line maps the different Bragg wavelengths of the FBGs into RF delays. To extract the values of these delays, the generated electrical current after photodetection is directed to the input port of the VNA where the electrical frequency response of the system is determined. This electrical frequency response has the form:

$$H(\Omega) = \sum_{k=0}^{N-1} a_k e^{-j\Omega\tau_k} \quad (1)$$

where Ω is the angular frequency, N is the number of reflectors, a_k is the sample weight and τ_k is the sample delay. Each sample weight is related to the FBG reflectivity whereas τ_k is a function of the FBG center wavelength thanks to the dispersive media, $\tau_k = \tau(\lambda_{Bk})$. It is clear that the electrical frequency response (1) is the summation of N oscillations in frequency, thus being possible to retrieve the sample delays through calculation of the IFT as the peaks' centers in the system's impulse response. In addition, a variation in the k -th Bragg wavelength amounts to a change in the corresponding delay according to the dispersion D of the dispersive delay line at that wavelength,

$$\frac{d\tau_k}{d\lambda} = D(\lambda_{Bk}) \quad (2)$$

The VNA determines the system's electrical response $H(\omega)$ in a positive frequency range $0 < \Omega < 2\pi B$, with B the measurement bandwidth in hertz. The IFT of this (single-sided) frequency response is given by:

$$h_B(t) = B \sum_{k=0}^{N-1} a_k e^{-j\pi B(t-\tau_k)} \text{sinc}[B(t-\tau_k)] \quad (3)$$

where $\text{sinc}(x) = \sin(\pi x)/(\pi x)$ and the peak positions determine the sample delays. Any change in the wavelength of one or several FBGs can now be determined as a delay change in each of these peaks.

The acquired traces by the VNA are in fact discrete versions of the amplitude and phase of the system electrical response $H(\Omega)$. If the IFT is calculated from $H(\Omega)$, the discrete nature of this electrical frequency response implies that, after IFT, the calculated impulse response $h_B(t)$ is also discrete, and the temporal separation between two consecutive sampling points, $\Delta t = t_{n+1} - t_n$, depends inversely with the measurement bandwidth, $\Delta t = 1/B$. In addition, from (3) it follows that what

is actually determined from the IFT is a temporally sampled version of a series of *sinc* peaks, whose width between zeros is equal to $2/B$ and thus of the order of the temporal spacing provided by the IFT.

To illustrate this problem, we have simulated the complete system in Fig. 1, with four FBGs in cascade and a chirped FBG dispersion of -170 ps/nm. The four FBGs have their Bragg wavelengths equally spaced between 1550 nm to 1553 nm with a 1 nm spacing. The measurement bandwidth was set to 10 GHz ($\Delta t = 0.1$ ns) and the frequency traces $H(\Omega)$ simulated with 2501 points. The Bragg wavelength of the third FBG was successively shifted from 1552 nm to 1551.95 nm and then to 1551.9 nm, in order to simulate a certain environmental change. The impulse response was numerically computed using the IFT. As can be seen in Fig. 2, the Bragg wavelength shift induces a change in the peak position of the impulse response, but this delay shift cannot be resolved by measuring the center (maximum) of the *sinc*, since it is the same at the three situations. The coarse sampling in the impulse response means that this small Bragg shifts instead of being shown as delay shifts are being shown as amplitude variations.

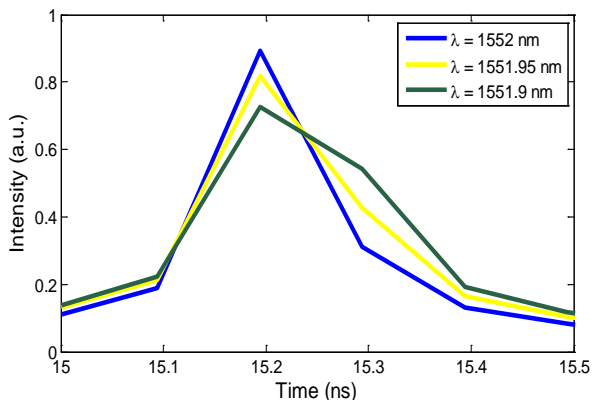


Fig. 2. Representation of the sample generated by an FBG when the impulse response is coarsely sampled.

In the previous work [9] we showed that using the standard zero-padding technique to interpolate this coarsely-sampled impulse response, resolution can be improved. This technique consists basically in adjoining zeroes to the raw VNA data traces to numerically increase the measurement bandwidth, reducing the temporal distance between consecutive sample points in the impulse response. This approach showed a good behavior since the resolution on this measurement depends on the ability to determine the center of the *sinc* peak, determination that is improved thanks to a smaller distance between consecutive points. The main drawback of this approximation was the large computational effort necessary to compute the IFT of zero-padded data.

The determination of the Bragg wavelength shift without filling the raw VNA data with zeros improves the effectiveness of the measurement, effectiveness that can be achieved making use of the Karhunen-Loeve transform (KLT). The KLT makes it possible to follow the amplitude

variations shown in Fig. 2, relating those variations with Bragg wavelength or temperature/strain variations thanks to the eigenvalues calculated by the KLT routine.

The KLT routine starts with the determination of the position of the maximum of each of the *sinc* peaks that represent the delays of each one of the samples generated by each FBG. As the number of points with which the routine has to work is 2501 points this determination is really fast. The next step is to select the four points that best represent the *sinc* peak of the FBG. Then the KLT routine is applied to these points, following the Maccone's procedure [13]. As is shown in Fig. 4, it starts with the calculation of the fast Fourier transform (FFT) of the four points selected, which is presented as a vector $\mathbf{G} = [G(f_1), \dots, G(f_4)]$, followed by the construction of the associated Toeplitz matrix $\mathbf{M} = (M_{ij})$. This is a 4×4 square matrix where the diagonals are constant from left to right such that $M_{ij} = G(f_{i-j+1})$. Next step is to apply the KLT routine core to the matrix \mathbf{M} . This is based on the determination of an orthonormal basis \mathbf{V} of the matrix \mathbf{M} which can be calculated easily performing the singular value decomposition (SVD) to the matrix \mathbf{M} :

$$\mathbf{M} = \mathbf{VDV}^{-1} \quad (4)$$

where \mathbf{D} is a matrix that contains in its diagonal the four eigenvalues of \mathbf{M} . The amplitude of the highest-rank eigenvalue of this set, records the amplitude change of the *sinc* peak allowing measuring the wavelength change continuously. As an example, the Bragg wavelength of the third simulated FBG was shifted from 1552 to 1556 nm with a 10 pm step and, as can be seen in Fig. 3, the highest eigenvalue $\xi \equiv \xi_1$ follows that wavelength change. It has a periodical behavior with a period of around 600 pm, so that the ξ value cannot track the Bragg wavelength beyond this period and an initial coarse determination of the Bragg wavelength must be performed. This could be achieved easily with a centroid estimation in order to locate the eigenvalue in the correct period, followed by the fine calculation of the Bragg wavelength change using the more accurate KLT routine, as schematically shown in Fig. 4.

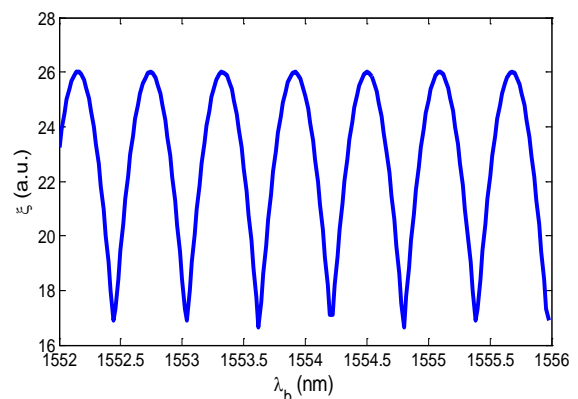


Fig.3. Highest eigenvalue calculated in the simulation test for different Bragg wavelengths.

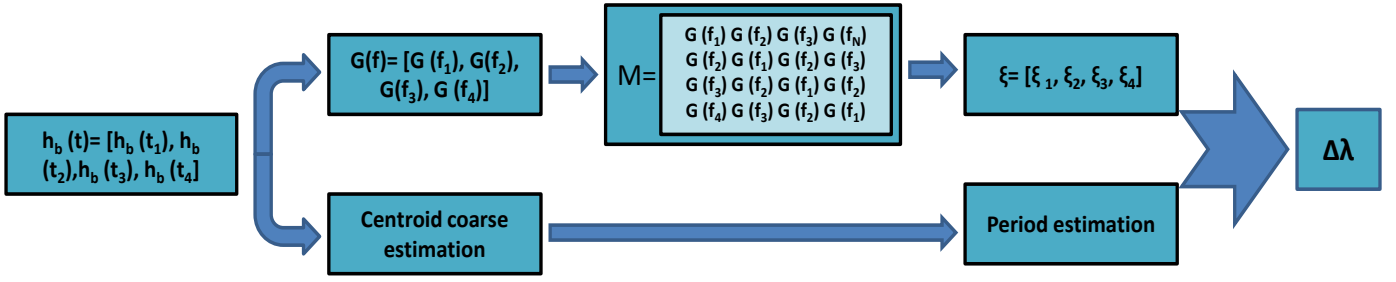


Fig.4. Flowchart of the KLT routine

This eigenvalue period is related to the RF measurement bandwidth in the capture of the electrical frequency response $H(\Omega)$ and the wavelength to time delay mapping scale. As mentioned above, the temporal interval between consecutive points in the impulse response, Δt is 0.1 ns for the bandwidth B of 10 GHz employed in our simulations. Using now that the chirped FBG provides a dispersion of -170 ps/nm, we arrive to the result that the period of the eigenvalue in terms of Bragg wavelength change is 588 pm. This means that the KLT can follow a variation of around 60°C within a single period, assuming a standard temperature coefficient of an FBG with Bragg wavelength around 1550 nm of $\delta\lambda_B/\delta T \approx 10$ pm/ $^\circ\text{C}$. The eigenvalue period can be increased either by decreasing the RF measurement bandwidth, B , or the value of dispersion, D .

III. EXPERIMENTAL MEASUREMENT

The setup shown in Fig.1. was mounted in our lab in a room in order to experimentally demonstrate that the KLT routine is able to measure temperature changes below the resolution of the measurement. It is clearly understandable that one of the key points of the good behavior of this interrogation technique is the constant dispersion of the dispersive media, a chirped FBG in our case. If this slope is not constant, the error introduced in the measurement could be higher than the resolution desired. So it is an important matter to have a good quality dispersive element as well as it is important to have it controlled in temperature and strain keeping its dispersion fixed. The dispersion of the CFBG used for the setup is -170 ps/nm and the delay variation is under 3 ps.

Another key part for the good implementation of this interrogation technique is the source used. As it can be seen in the previous page the KLT routine converts amplitude variations of the sample created by an FBG in wavelength shifts due to temperature or strain variations. So a fluctuation in the power of the light that is being injected in the system by the source will be translated in a wavelength change when no temperature change is being suffered by the FBG. The source used in the real experiment is a C&L band amplified spontaneous emission (ASE) source from NP Photonics, which has a 0.01 dB power variation when the temperature is constant.

The temperature of the setup room was being kept constant in order to maintain the dispersion of the chirped FBG imperturbable. Four FBGs were written in the same fiber coil with a 1m separation approximately to perform the role of multiplexed sensor. These FBGs had their wavelengths inside

the 20nm bandwidth of the chirped FBG as it is shown in Fig.5.

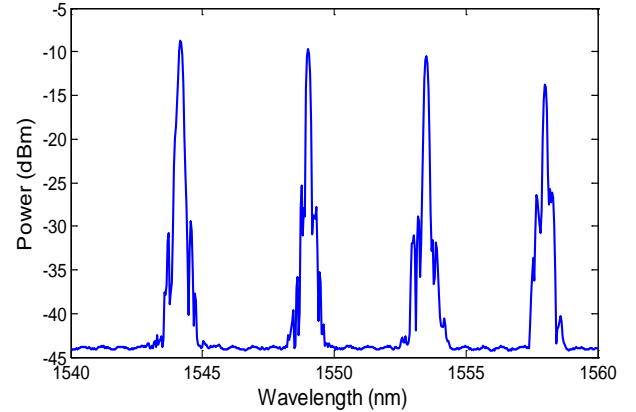


Fig.5. Reflection spectrum of the FBGs used as multiplexed sensor

As can be seen the wavelengths of the FBGs are equally spaced inside the 20nm bandwidth and their reflectivity is not equal. The last FBG, whose central wavelength is around 1558 nm, was fixed inside a climatic chamber in order to produce a ramp temperature variation. The procedure was as it follows:

- 1) The first step was to switch on the climatic chamber and set its objective temperature to -20°C .
- 2) Once the climatic chamber has arrived to -20°C temperature value is important to keep it at that level for some time in order to homogenize the temperature inside the climatic chamber and to avoid the appearance of temperature gradients.
- 3) After the climatic chamber has been at -20°C for some time the climatic chamber is switched off in order to avoid vibration problems during the measurement and keep it in that way for 20 minutes in order to homogenize the temperature inside the chamber and avoid again temperature gradient and air currents.
- 4) Once the temperature is constant inside the climatic chamber the measurement series starts.
- 5) The electrical response of the system is recorded thanks to the VNA when the temperature suffers an increment of 0.5°C . The increment of the temperature is really slow and it is produced by the temperature difference between the room and the climatic chamber. This makes the temperature change really smooth avoiding temperature gradients and air currents inside the chamber, phenomena that could affect the behavior during the measurement set.
- 6) The last step is the calculation of the IFT of the electrical response in order to retrieve the system impulse

response and the implementation of the KLT routine for the measurement of the temperature variation following the amplitude change of the FBG sample.

The electrical frequency response was recorded with a frequency span from 0-2.5 GHz so the temporal distance between consecutive points in the impulsive response is $\Delta t=0.4\text{ns}$, which means that the period of the eigenvalues calculated by the KLT routine should be around 2353 pm, thus the increment of temperature needed to cross a complete period would be $\approx 235^\circ\text{C}$.

If the KLT routine was not used, the resolution of this measurement would be this 2353pm since the ability to measure a temperature change would be the capacity of measure a change in position of the maximum of the sinc peak event that only occur when the Bragg wavelength shift a 2353 pm quantity. So we would have to change the temperature around 235°C to measure a unique change.

The measurement set began with a climatic chamber temperature of -16.5°C and it last until the climatic chamber reached -1°C . As can be seen is only a temperature change of 15.5°C , impossible to notice if the KLT routine was not being used, but as can be seen in Fig.6. the highest eigenvalue calculated by the KLT routine is following the temperature changes with a resolution that is under 0.5°C .

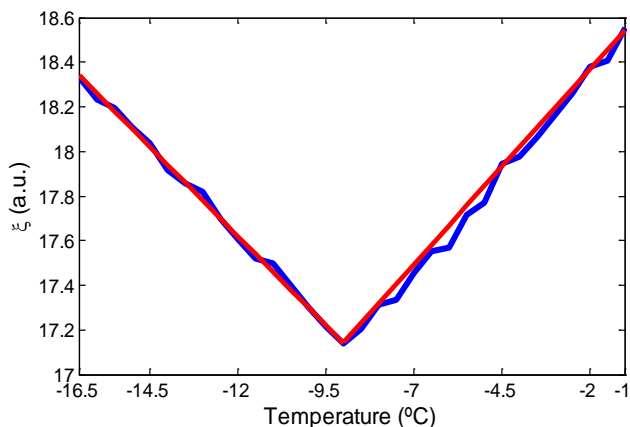


Fig.6. Highest rank eigenvalue calculated by the KLT routine for the sample generated by the FBG fixed inside the climatic chamber (blue trace) and linear fitting (red trace)

To have this resolution making use of the zero padding technique the temporal distance between consecutive points in the impulse response (2) should be 0.85ps , which means an equivalent measurement bandwidth of 1176.5GHz . To achieve this equivalent bandwidth we should have to insert around 500 zeros per each raw VNA data point in order to achieve the same resolution, making the interrogation technique much less competitive computationally speaking.

Another thing to highlight from Fig.6 is that the eigenvalue behavior is not as linear as it was expected. This misbehavior is due to the coarse 1°C accuracy of the temperature value measured by the climatic chamber. Comparing the measured trace with the linear fitting depicted as a red trace in Fig.6, the maximal temperature error introduced is lower than 0.4°C . Source power fluctuations, modulator Q-point drifts and dispersion changes of the chirped FBG are expected to be minimal since the temperature was controlled in the room along the entire experiment.

IV. CONCLUSIONS

In this paper, the Karhunen-Loeve transform is used to retrieve the sensing information of a multiplexed sensor formed by four FBGs in cascade. The working principle of the system is based on the use of a filtering microwave photonics technique to record the Bragg wavelengths of several FBGs in cascade in the radio-frequency delays on the impulse response of the fiber optics link. This wavelength mapping is performed by a dispersive media, role played by a chirped FBG. The radio-frequency waves generated by a VNA modulate the light coming from a broadband source in the electro-optic modulator in order to capture the electrical frequency response of the system. Through IFT calculation the impulse response of the system is retrieved, impulse response where the FBG samples are embedded in a *sinc* peak. Thanks to the coarse sampling in the impulse response, the *sinc* shaped samples are depicted only by four points, causing that any environmental change would be seen as an amplitude sample shift instead of a sample delay shift. These amplitude changes are followed by the eigenvalues calculated by the KLT routine, allowing to measure continuously the temperature change although the delay change produced is smaller than the temporal resolution in the impulse response.

The measurement resolution does not depend in the RF bandwidth or the dispersion as in the previous work presented. These parameters are important in order to ensure that the delay samples are not overlapped, it is to say not aliasing is present in the impulse response.

This interrogation technique has been experimentally demonstrated with a fiber link where four FBGs with different wavelengths and reflected power are written. A temperature change smaller than the resolution given by the temporal distance between consecutive points in the impulse response has been produced, proving that the KLT routine improves the resolution of the system without need to insert zeroes in the raw VNA data. Temperature changes of 0.5°C (Bragg wavelength changes of 5 pm) have been followed by the highest eigenvalue calculated by the KLT routine, reducing by a 500 fold the number of points needed to do so with the previous technique presented.

An increment in the number of sensors only implies a small increment in the computational complexity and measurement time, since the electrical spectrum measurement and IFFT calculation time are not dependent on the amount of sensors. Once the impulsive response has been calculated only four points are needed for the correct interrogation of each sensor.

Finally, it is important to notice the advantages of this new interrogation technique over conventional interrogation methods based on tracking the Bragg wavelength of the FBG in the optical spectrum. In particular, the present technique does not require tunable sources or receivers, showing at the same time an improvement in the accuracy of wavelength determination to the sub-pm level [8] and the possibility to demodulate arrays of FBGs with the same nominal wavelength.

REFERENCES

- [1] K. Grattan and T. Sun, "Fiber optic sensor technology: an overview," *Sens. Actuators A Phys.*, vol. 82, pp. 40–61, May, 2000.
- [2] A.D. Kersey, "A review of recent developments in fiber optics sensor technology," *Opt. Fiber Technol.*, vol. 2, pp. 291–317, Feb. 1996
- [3] J. Hervás Peralta, A. Ricchiuti, D. Barrera, S. Sales, L. Thévenaz, and J. Capmany, "Weak fiber Bragg grating cascade sensor interrogation using microwave photonic filtering techniques," in *Advanced Photonics*, OSA Technical Digest (online) (Optical Society of America, 2014), paper SeW1C.2.
- [4] L. Thévenaz, S. Chin, J. Sancho, and S. Sales, "Novel technique for distributed fibre sensing based on faint long gratings (FLOGs)," *Proc. SPIE*, vol. 9157, 23rd International Conference on Optical Fibre Sensors, 91576W (June 2, 2014).
- [5] M. Tateda and T. Horiguchi, "Advances in optical time-domain reflectometry," *J. Lightw. Technol.*, vol. 7, no. 8, pp. 1217-1224, Aug. 1989.
- [6] K. Yuksel, *et al.* "Optical frequency domain reflectometry: A review," presented at *11th International Conference on Transparent Optical Networks*, 2009.
- [7] A.L Ricchiuti, D. Barrera, S. Sales, L. Thévenaz, and J. Capmany, "Long fiber Bragg grating sensor interrogation using discrete-time microwave photonic filtering techniques," *Opt. Express*, vol. 21, pp. 28175-28181, Nov. 2013.
- [8] D. Tosi, "KLT-based algorithm for sub-picometer accurate FBG tracking with coarse wavelength sampling", *IEEE Phot. Tech. Letters*, vol. 27, no. 20, pp. 2134-2137, Oct. 2015.
- [9] J. Hervás, C. R. Fernández-Pousa, D. Barrera, D. Pastor, S. Sales and J. Capmany, "An Interrogation Technique of FBG Cascade Sensors Using Wavelength to Radio-Frequency Delay Mapping", *J. Lightw. Technol.*, vol. 33, no. 11, pp. 2222-2227, June 2015.
- [10] E. J. Ahmad; C. Wang; D. Feng; Z. Yan; L. Zhang, "High spatial and temporal resolution interrogation of fully distributed chirped fiber Bragg grating sensors," in *J. of Lightw. Technol.*, vol. PP, no. 99, pp.1-1, 2016.
- [11] R. Cheng, L. Xia, Y. Ran, J. Rohollahnejad, J. Zhou and Y. Wen, "Interrogation of Ultrashort Bragg Grating Sensors Using Shifted Optical Gaussian Filters," in *IEEE Phot. Technol. Letters*, vol. 27, no. 17, pp. 1833-1836, Sept. 2015.
- [12] Choi, S.J., Mao, W., Pan, J. K., "Novel RF Interrogation of a Fiber Bragg Grating Sensor Using Bidirectional Modulation of a Mach-Zehnder Electro-Optical Modulator," *Sensors*, vol. 13, pp. 8403-8411, July 2013.
- [13] C. Maccone, "Advantages of Karhunen–Loève transform over fast Fourier transform for planetary radar and space debris detection," *Acta Astronaut.*, vol. 60, nos. 8–9, pp. 775–779, May 2005.