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Monitoring temperature and vibration in a long weak grating array with short-pulse generation using a compact gain-switching laser diode module

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Abstract: Quasi-distributed temperature sensing and single point vibration sensing were performed. Ultrashort pulses generated by a gain-switching laser were used to interrogate a fiber Bragg gratings (FBG) array sensor. Temperature changes were measured down to 1°C with sub-centimeter spatial resolution. The advantages of our fast interrogation setup were exploited, as the higher frequency limit of a dynamic measure that can be sensed is limited by the time needed to generate the optical pulse and to acquire the data from the sensor. The experimental approach described in this paper can sense mechanical vibrations up to a frequency of 245 kHz and a strain resolution as low as 1.2 $\mu\varepsilon$.

1. Introduction

FBG based sensors are now consolidated methods of measuring temperature and strain. The most frequently used FBG technique is by employing tunable laser and photodetector to retrieve the spectrum of the FBG in the wavelength domain. As the FBG spectrum shifts when a temperature or strain variation is exerted on the grating region, it is necessary to estimate the peak wavelength (known as Bragg wavelength) from the FBG spectrum and then to track its shift from the reference position to effectively use an FBG to estimate a temperature or strain variation [1]. This method can reach a resolution of 10 pm/°C [2] for temperature measurement. One single grating inscribed on a fiber can sense temperature or strain at one point. In order to sense at multiple points using peak tracking and a single fiber, FBGs must be inscribed with different Bragg wavelengths and every peak must be tracked independently. This method is commonly known as *wavelength division multiplexing* (WDM) [3]. However, this technique has certain drawbacks: firstly, the inscription of gratings with different wavelengths is not a cost-effective solution, it limits the maximum number of independent points that can be monitored in a single fiber and dense arrays of FBGs cannot be produced to implement a quasi-distributed sensing system. Secondly, the time required to sweep the tunable laser limits the maximum frequency of a detectable dynamic refractive index change.

A time-based analysis enables the use of distributed and quasi-distributed fiber-based sensors. In this field, the phase sensitive OTDR offers many advantages when performing distributed sensing, with high spatial resolution and the possibility of interrogating many kilometers of fiber [4]. This sensing technique can coherently sense the Rayleigh backscattered signal in single mode fibers by exploiting the OTDR classical setup and constant phase light pulses. As the backscattered signal is quite low powered (<−70 dB/m), highly sensitive photodetectors must be used. Distributed sensing in fiber is mostly used for long fiber sections and this technique can sense dynamic strain at frequencies of up to 39.5 kHz with a spatial resolution of 5 meters in 1.25 km of fiber [5]. Commercial distributed temperature sensor interrogator achieves a spatial resolution of 12 cm over 50 km [6] and 25 cm over 40 m for acoustic sensing (frequency range

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0.01 Hz-50 kHz) [7]. Optical frequency domain reflectometry (OFDR) has also been used to sense vibration in single mode fibers. In this case the need to sweep a laser over a long wavelength range further limits the maximum frequency that can be sensed. OFDR systems achieve a spatial resolution of 10 μm for temperature sensing over 2 km of fiber while a resolution of 10 μm in dozens of meters for dynamic strain measurement with a maximum sampling frequency of 3 Hz [8].

Implementing a system to perform distributed sensing by FBGs would require the grating to be inscribed along the length of the sensing fiber [9]. The idea is to enhance the back-reflected signal in fiber using a weak uniform grating. The production of such a device is still a challenge but draw tower gratings are a good alternative. These gratings are created during the drawing process of the optical fiber [10] and make it possible to produce long arrays with a large number of FBGs. If the FBGs are densely assembled in the array a higher backscattered signal can be obtained (as in using a Faint Long Optical Grating [9]) and a quasi-distributed sensor can be implemented. Multipoint sensing with FBG arrays has been reported in the literature, for example in [11], which describes an interferometric technique on an array of near-identical weak gratings. Microwave filtering photonic techniques have also been used to interrogate a weak grating array [12] and a long weak grating [13].

In this work we used a dense array of 500 0.9 cm long weak gratings separated by 0.1 cm interrogated by a short laser pulse to reach high spatial resolution. The higher back reflected signal made it possible to use a photodetector with a lower sensitivity than that required for phase sensitive OTDR. The spatial position of the hot point is calculated on the temporal trace by time of flight. The laser used is a gain switching laser that generates pulses of less than 10 ps without an external electro optical modulator (EOM) [14]. The pulses have a high extinction ratio and low jitter, which is essential to correctly recover the reflected signal evolution in time. Even though the gratings are very weak (nominally around 0.1% reflectivity) the back-reflected signal is clearly higher than the Rayleigh backscattering.

Two different measurements were made with the same setup. The signal was acquired in the time domain with an optical oscilloscope for quasi-distributed temperature sensing with sub-centimeter spatial resolution on an FBG array. The second application was the measurement of dynamic strain (mechanical vibration) sensing. Many studies in the literature have proposed techniques to sense dynamic measurands as vibration using optical fibers. In [15] Cusano et al. describe an interrogation setup using a super-luminescent diode and a grating-based passive filter that can measure vibrations of up to 50 kHz. In [16] two FBGs are used to implement the interrogation system: one to generate a narrow-band signal in wavelength from an incoherent light source and another as a sensing element. A narrow source distributed feedback laser diode (DFB-LD) is used in [17] as the light source to interrogate the FBG vibration sensor. In [18] a fiber ring laser is used to implement the interrogation system of a vibration sensor. Due to the Shannon principle, the factors that limit the maximum frequency in dynamic measurements are: laser sweep time (as for the wavelength in WDM), time of flight of the optical pulse in fiber (significant for long fiber sections) and speed of the electronic front end that acquires the signal. The advantage of the system proposed here is that the laser always emits around the Bragg wavelength of the gratings in the array. The vibration signal is obtained by detecting the reflected optical signal with a fast avalanche photodiode. A simple demodulation is used to interrogate the strain-induced Bragg wavelength shift. The proposed interrogation system can measure vibration and reach measured mechanical vibrations of up to 245 kHz with a strain resolution of 1.2 $\mu\varepsilon$.

2. Interrogation setup and principle of operation

The interrogation technique described here is a wavelength-to-time domain analysis implemented with a gain-switching laser diode module [14]. Gain switching (GS) of a distributed feedback semiconductor laser diode is widely used to generate short optical pulses for time-division

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multiplexed optical communication systems, soliton generation and optical signal processing [19]. This compact and reliable module uses an attached fiber cavity whose ends are coated with diamond-like carbon (DLC) as a self-seeding pulse feedback circuit (Fig. 1).

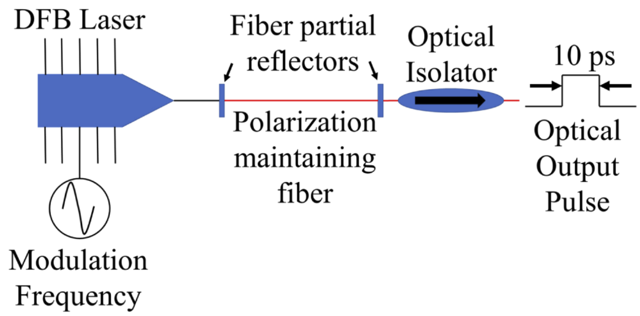

Fig. 1. Laser module and optical fiber cavity used for gain-switching implemented with polarization maintaining fiber and two partial reflectors.

The DFB-LD is wavelength-tuned by a temperature controller: the wavelength of the tunable laser used to perform the measurements had previously been temperature calibrated, so that by simply adjusting the thermistor resistance controller the laser wavelength can be easily tuned. The central frequency of the interrogating pulse is precisely controlled by the injection current applied to the laser. The only external signal needed to activate the self-seeding mechanism, and thus the pulse generation, is a square wave at 5.9 GHz, a much lower frequency than that required to drive an external modulator to generate 10 ps pulses by direct modulation. The setup consists of the laser described above, a dispersion element that introduces −171 ps/nm (at 1550 nm) and an array of 500 weak FBGs (Fig. 2). The reflected signal was acquired using an oscilloscope with an optical sampling module. The acquisition of the back reflected signal was triggered by the modulation signal that generates the laser pulses.

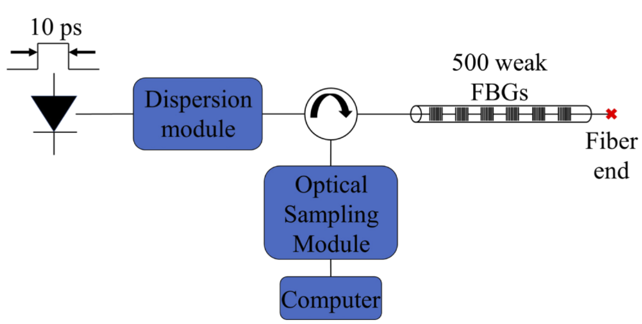

Fig. 2. Scheme of the interrogation system and array of 500 weak FBGs.

The dispersive element consists of a dispersion-compensation module. The output laser pulse has a short time duration and a broad wavelength spectrum (approximately 1 nm). The dispersion linearly separates the wavelengths of the spectra of the light pulse in time. The pulse-like signals reflected by the single FBGs carry the amplitude and time delay information associated with the spatial position and Bragg wavelength of each grating. Two events can occur between two instants in time: if no change in the central wavelength is caused by a change in temperature and/or strain, the amplitude and delay of the reflected pulse do not change. If there is a change in the refractive index, the pulse experiences a time shift and a change in amplitude. In order to demonstrate this principle, a Bragg wavelength shift was caused with temperature. Figure 3(a)

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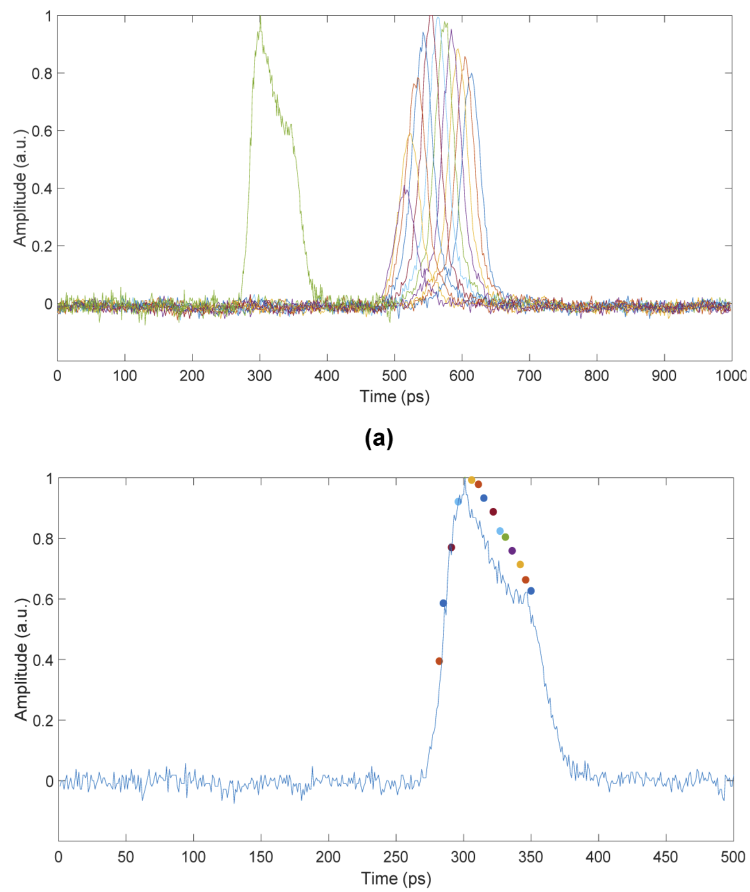

Fig. 3. (a) Interrogation pulse after the dispersion element (green line) and back reflected pulse from an FBG at different temperatures. (b) The points represent the maximum of the peaks plotted in Fig. 3(a) superimposed to the interrogation pulse (blue line).

shows the plot of the laser pulse after the dispersion element and the reflected pulses (of one FBG) at different temperatures. The maximum of the peak was plotted and superimposed on the interrogation pulse to clearly show the correspondence (Fig. 3(b)).

3. Temperature measurement

When a hot zone is created along the FBG array a temperature gradient is obtained. This local change of temperature will produce a local Bragg frequency shift. The hot point on the array, approximately 1 cm long, was obtained using a closed loop temperature controller implemented with a Peltier and thermistor. The temperature was swept from 10°C to 40°C. The nominal shift of the FBGs in the array with temperature is 10 pm/°C. To obtain the expected dependence of the temporal shift with temperature we multiply this wavelength shift by the dispersion at the laser frequency, obtaining an expected value of 1.702 ps/°C. The hot point was moved along the grating array to interrogate two consecutive gratings (separated by about 1 cm) and verify the sub-cm spatial resolution achieved. Figure 4 shows the reflected spectrum of 6 weak gratings around the hot point when the temperature is swept from 10°C to 40°C in 3°C steps. The interrogation pulse has a lower wavelength at the end of the pulse in the time domain. When the temperature is

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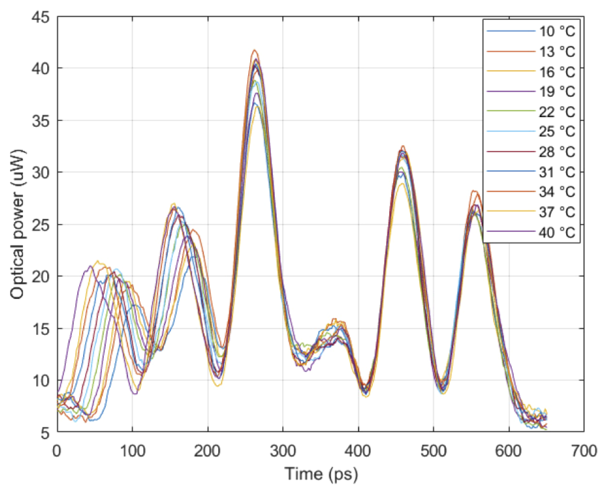
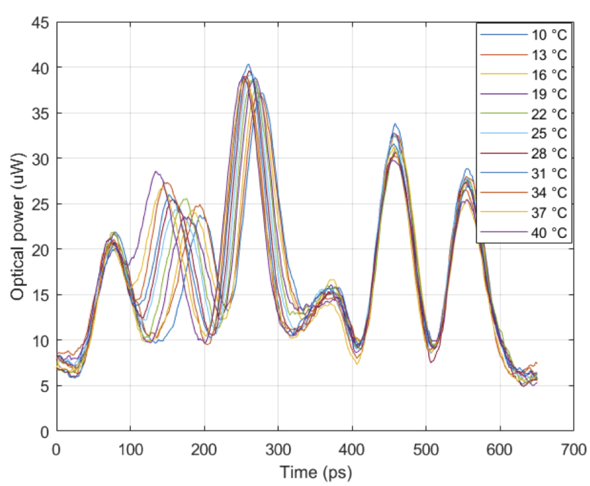
lowered the resonant wavelength of the gratings moves to a lower wavelength, producing a delay of the trace around the hot point.

Figure 4 shows the traces of the reflected signal when the temperature sweep is applied at one point (Fig. 4(a)) and moved to another grating in the array (Fig. 4(b)). The resolution given by the pulse width allows the two cases to be clearly distinguished. This system could not only sense the temperature at the hot point, but also the temperature gradient along it as a gradual reduction of the time shift when we moved away from the hot point.

To evaluate the linearity of the time shift with temperature, a threshold was fixed to a certain optical power and the time stamp of consecutive traces was derived (Fig. 5(a)). The result and the graphic description of the method used are shown in Fig. 5. The absolute time stamps of the traces are linear with temperature (R = 0.99389) (Fig. 5(b)). The mean value and the standard



(a)



(b)

Fig. 4. Reflected signal of the array portion under test. The two images show the heating of two points (first point showed in (a), second point showed in (b)) less than one centimeter apart. In both cases the time shift is visible due to the temperature rising from 10°C to 40°C.

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deviation of the measured time shifts were 1.9 ± 0.3505 ps, close to the expected value of 1.7 ps. The standard deviation is quite high due to the uncertainty of measuring the absolute temperature of the sample with an accuracy better than ± 0.25°C in our lab conditions.

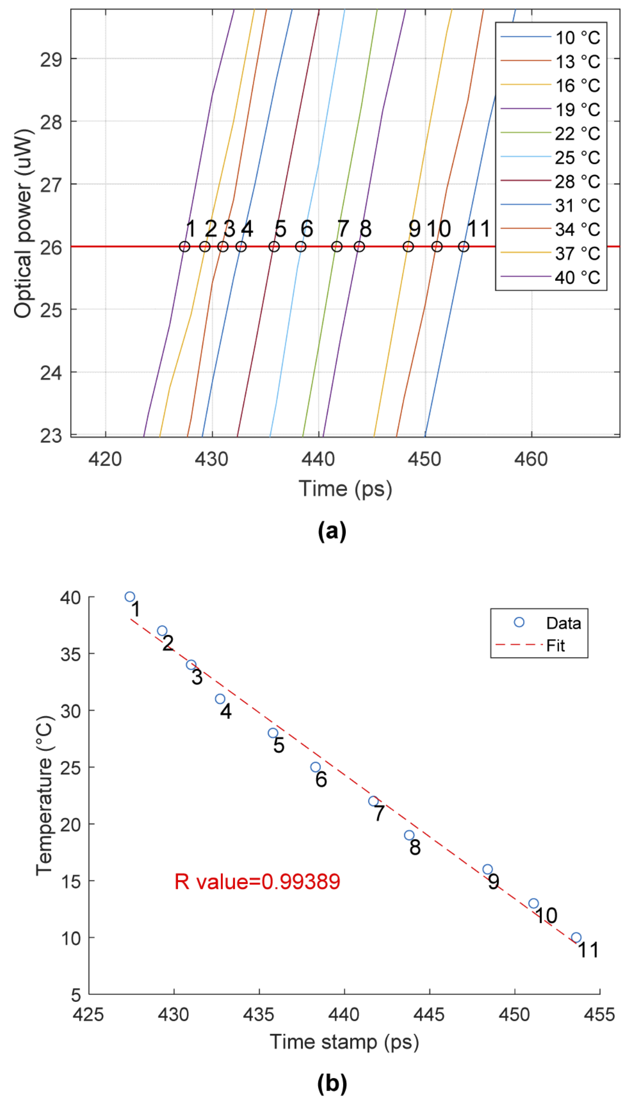

Fig. 5. (a) Evaluation of the response of the sensor to temperature. (b) When the temperature was swept from 10°C to 40°C there was linear relation between time stamps and temperature.

4. Vibration measurement

As explained in the Introduction, the speed of the interrogation system (the sum of the time needed to generate the optical pulse and the acquisition time of the reflected signal) limits the maximum frequency of a dynamic measurand. Since the only active element is the pulsed laser, and the dispersion is added to the interrogation pulse with a passive dispersive element (no active tuning of the laser wavelength is employed), we deduced that our setup could sense dynamic Bragg wavelength shift at high frequency. The only modification in the setup is that the reflected

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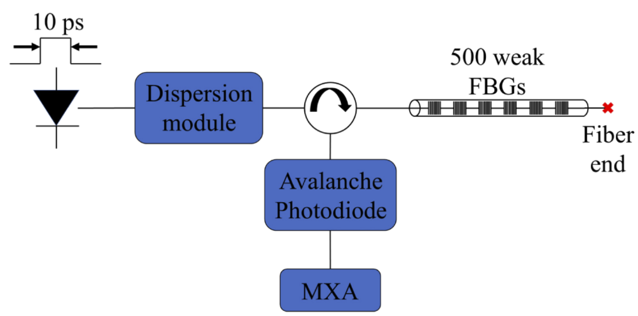
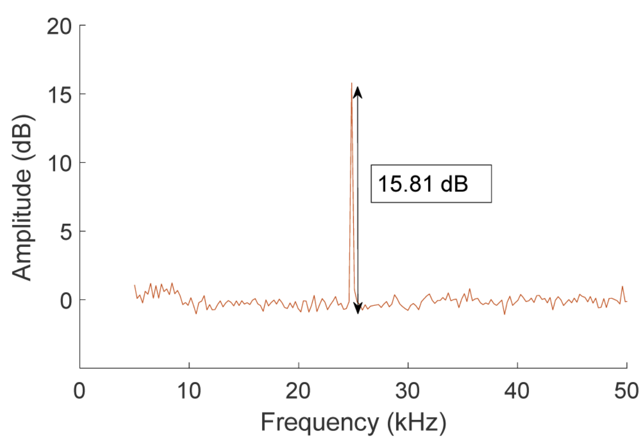
signal is now fed to an avalanche photodiode (Thorlabs APD430), which can sense dynamic change in the optical signal from DC-400 MHz. The APD electric output is connected to an electric signal analyzer (MXA) (Fig. 6(a)). There is a trade-off in the choice of the spectrum width of the light source: a wide spectrum allows to have a high temperature range but affects negatively the strain resolution for vibration sensing. We chose a wide light source with a non-flat spectrum. As it can be observed in Fig. 3, the amplitude distribution along the pulse has a triangular shape. This spectral feature allows to have an amplitude modulation, that the APD can sense, when a dynamic strain is applied. The reflected optical signal is constant until a dynamic strain is exerted on the fiber grating. A portion of the sensing element (approximately 5 centimeters) was glued to a piezoelectric (PZT). 10 volts were applied to the PZT, which correspond to a fiber strain of 38 $\mu\varepsilon$. The result of an applied vibration at 25 kHz is shown in Fig. 6(b). The measurement was obtained using a resolution bandwidth of the electric spectrum analyzer of 51 Hz. At this frequency the signal is 15.18dB over the noise level. An estimated strain resolution of 6.16 $\mu\varepsilon$ is achieved at this frequency (if we consider the 30dB achieved at 155 kHz, for example, a resolution of 1.2 $\mu\varepsilon$ is obtained).



(a)



(b)

Fig. 6. (a) Scheme of the interrogation system. (b) Recovered spectra of the photodetector electrical output when a vibration of 25 kHz is applied to the sensing element.

The frequency of the PZT was swept in steps of 10 kHz between 15 kHz and 245 kHz, even for these measurements the resolution bandwidth was of 51 Hz. Figure 7 shows the signal traces of the electrical spectrum analyzer at different frequencies of the PZT performing 10 averages.

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In the frequency range tested, the signal goes from 10 to 30dB above the noise level, with an obtained resolution between 1.2 $\mu\varepsilon$ and 12 $\mu\varepsilon$.

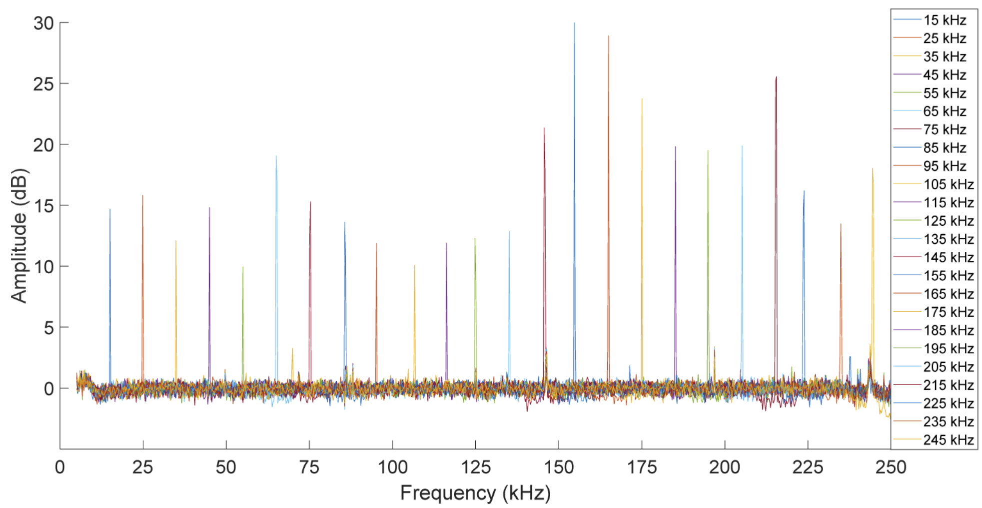

Fig. 7. Frequency spectra of the photodetector electrical output when the frequency of the vibration is swept between 15 kHz and 245 kHz.

5. Conclusions

This paper proposes a quasi-distributed sensing system of a 5 m long weak grating array, using a compact pulsed laser module without an external EOM. The dispersion added to the interrogation pulse can convert any Bragg wavelength shift inside the 500 weak grating arrays in a time shift. A long array of FBGs produced at the same wavelength could be interrogated independently. The weak gratings reflect part of the signal and allow to measure the temperature and vibration at the same time. Simultaneous sensing of temperature and vibration could be performed separating, in the frequency domain, the low frequency temperature changes and the high frequency vibration signals. The system's sensitivity was limited to 1°C due to the maximum sampling rate (2 ps) of the oscilloscope, with a spatial resolution of 1 mm. Temperature sensitivity can be enhanced by applying a higher dispersion to the pulse and using a detection system with a higher sampling rate. Vibration sensing was performed on the same setup, a portion of the sensing element (approximately 5 centimeters) was glued to a PZT. 10 volts were applied to the PZT, which correspond to a fiber strain of 38 $\mu\varepsilon$. Mechanical strains as low as 1.2 $\mu\varepsilon$, changing in time to a frequency of 245 kHz exerted on a portion of the weak FBG array, were measured. There is a trade-off in the choice of the spectrum width of the light source: a wide spectrum allows to have a high temperature range but affects negatively the strain resolution for vibration sensing. We chose a wide light source with a non-flat spectrum, thus allowing to have an amplitude modulation when a dynamic strain is applied. The components used to implement the interrogation system for vibration, the pulsed laser module and the reflected signal photodetector are quite compact and allow the whole system to be implemented in a compact frame.

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Disclosures

The authors declare no conflicts of interest.

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