

Piezo acoustic versus opto-acoustic sensors in laser processing

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Abstract. Piezo acoustic sensors are well known in the field of acoustic emission since the 20's but are considered as a common product since the 70's. Since that time, the number, type, shape and temperature range of AE sensors have been broadened to satisfy the industrial demands. When considering either high temperature and/or small size, piezo acoustic sensors have limits and an alternative technology has to be considered. In industrial applications with special requirements to high temperature tolerance, small size ($< 150 \mu\text{m}$), broad frequency response, insensitive to electromagnetic interference, opto-acoustic sensors including Fibre Bragg Grating (FBG) are very good candidates.

FBG is an interferometric structure, imprinted inside the core of the optical fibre with unique spectral characteristics of reflectivity. The acoustic waves created during an industrial process result in periodical extension/compression of the optical fibre core and, consequently, the FBG structure. These momentary deformations affect the reflectivity properties of the FBG that follow the behaviour of the incoming pressure waves. This behaviour results in the intensity of the reflected light that encodes the momentary deformation states of the fibre core and so can be used for acoustic sensing. These sensors exhibit linear response in a broadband frequency range (from several Hz to tens of MHz) with potential detection upper limit of the order of several hundred MHz. In contrast, most piezo sensors have linear response in a limited bandwidth and lower detectable frequencies.

In this work, we will focus on the fibre technology and compare the sensitivity of commercial FBG with several piezo acoustic sensors. We will also show how FBG's can be used as acoustic sensors in laser processing by analysing the data with state-of-the-art machine learning techniques, in particular for classification of laser power made from the sample itself which can be related to its quality.

Introduction

This paper presents an investigation of using modified optical fibres; in particular Fibre Bragg Gratings (FBG) and phase-shifted FBG (PSFBG), as acoustic sensors. The sensitivity of FBG and PSFBG is also compared with several piezo acoustic sensors. To demonstrate the potential use of FBG in industrial process, they have been tested in laser processing for determining the laser power from the sample itself which can be related to the sample quality.

Optical fibre based sensors have been the subject of research for more than 40 years. The research has been driven by the attractive properties of the optical fibre platform



itself. It includes its small size, flexibility, immunity to electromagnetic interference, low loss, high temperature stability, high bandwidth, just to name a few. Among the large variety of optical fibre sensor technologies, the most researched and successful in both commercial and application terms has been the FBG [1].

Fibre Bragg Gratings can be considered as optical band rejection filters, or the equivalent of a one dimensional photonic crystal. Their function is the back-reflection of a narrow wavelength band of light and the transmittance of all other wavelengths propagating in the fibre core. FBGs are formed inside the core of an optical fibre by periodical spatial modulation of the refractive index. The period of the structure determines the central wavelength to be back-reflection according to Eq. (1) [2]:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \quad (1)$$

where λ_B is the reflected wavelength (Bragg wavelength), n_{eff} is the effective refractive index of the mode (related to the effective index of the propagating mode and affected by the magnitude of the induced refractive index change in the core), and Λ is the period of the refractive index modulation. Typically, such sensors are fabricated interferometrically by a laser side illumination of the optical fibre through a diffractive optical element (phase mask) that forms the periodic structure. A change in the periodicity of the FBG results in the shift of the Bragg wavelength, providing the sensing capabilities of the FBGs.

The detection principles of acoustic emission (AE) with optical fibres are based on two major techniques: optical fibre interferometers and FBGs [3]. The first reports of interferometer based optical fibre AE sensors date back to 1977 [4]. Ever since, numerous researchers have examined different varieties and implementation of those sensors. Despite their good sensitivity, optical fibre interferometers suffer from cross sensitivity, as the whole fibre length that transmits the signal can be affected by external factors and alter the measured signal. Short length interferometers, e.g. Fabry-Perot cavities [5], overcome this caveat but lack dynamic range and require careful handling, while, in most cases, lack any low-cost multiplexing capability.

FBG for AE detection are a more recent advancement (first proposed in 1996 [6]) and have been extensively researched in the last years, due to their attractive properties. The main ones are: the small size, multiplexing capability, chemical and electromagnetic/radiation neutrality, high temperature resistance (up to 1200°C for specific FBG). Also, the fact that the sensing element is ‘sealed’ around a glass jacket (the optical fibre cladding) makes FBG ideal for AE sensing in hostile environments. Besides, the availability of numerous optical fibre components off-the-shelf at a relatively low cost is another significant benefit for practical applications. Recent research in the field has exhibited FBG based setups with sensitivities up to 5 pε/Hz^{1/2} for frequencies larger than 100 kHz and detectable range up to 10 MHz [7], a performance which is similar or surpasses even interferometric setups. Moreover, the efforts to convert FBG sensitivity from omni- to uni-directional by cylindrical housings [8] were carried out with a large degree of success.

The utilization of FBGs in AE detection is typically realized either by using the power [9] or the edge filter detection method [10]. The former is comprised of a broadband light source coupled to a circulator that interrogates one or more spectrally separated FBGs. The back-reflected signal is routed to a demultiplexer that uses either a (spectrally) matched FBG or a narrow bandpass filter to extract the corresponding wavelength and supply the signal to a photodiode. This method is low cost, highly scalable in terms of sensor number and requires little maintenance, but at the cost of sensitivity.

On the other hand, the edge filter detection method is significantly more sensitive and, thus, used when ultimate detection sensitivity is required. A typical setup is comprised of the components presented in Fig.1: a narrow linewidth tunable laser (TLS), optionally an

isolator to protect the source from any light back-reflections, a 3 port circulator that feeds the FBG with light and routes the back-reflected signal to a photodiode (PD). Alternatively, a balanced PD can be used where both transmitted and reflected signals are monitored.

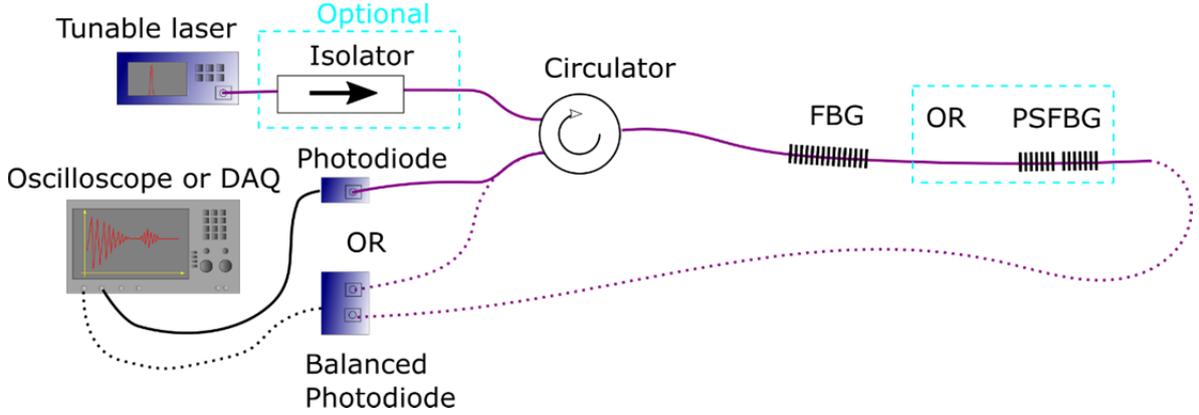


Fig. 1. Edge filter method setup for the detection of AE using FBGs or phase-shifted FBGs (PSFBGs). Dotted line connections refer to the case of using a balanced photodiode.

The working principle of the edge filter method is as follows. The TLS is set to a wavelength within the linear slope of the FBG spectrum (see Fig. 2a). Depending on the spectral positioning of the TLS, a certain amount of light is back-reflected from the FBG and fed into the PD resulting in an output signal (I_{PD}). An incoming acoustic wave will cause the FBG to vibrate ($\Delta\lambda_B$, see Fig. 2b), resulting in spectral blue and red-shifts. As the TLS wavelength is fixed, this will lead to a change in the amount of light back-reflected and consequently a variation in the PD signal (ΔI_{PD}) that is captured and recorded through an oscilloscope or a DAQ card. Graham and Hinckley have shown [11] that the use of a second PD to monitor both transmission and reflection signals can enhance the sensitivity of the method by removing part of the direct current (DC) noise originating from the laser intensity fluctuations. Alternatively, a balanced photodiode can be equally utilized.

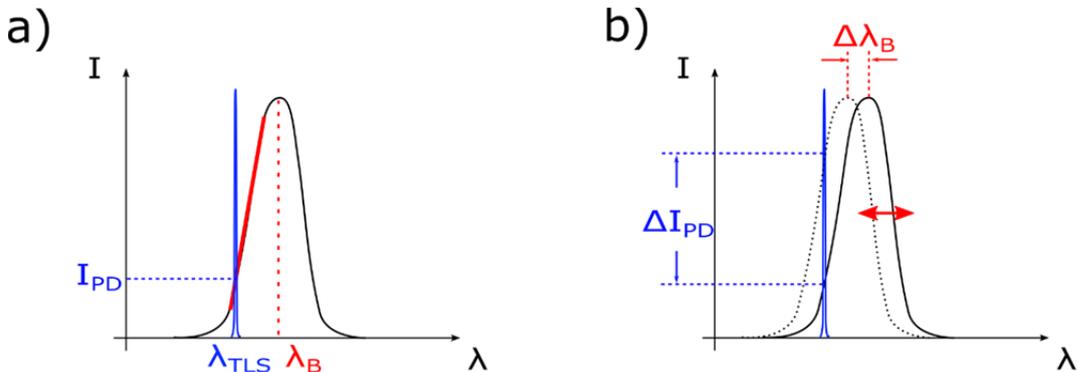


Fig. 2. Edge filter detection method working principle: (a) Tunable laser wavelength (blue line spectrum, λ_{TLS}) is set within the linear slope of the FBG spectrum (red line). (b) An incoming acoustic wave will cause the FBG to vibrate resulting in Bragg wavelength shifts and in turn changes in the intensity of the back-reflected signal.

The sensitivity of the method can be expressed mathematically using the formula presented by Wu and Okabe in [12]:

$$V_S = \Delta\lambda_B \cdot G \cdot R_D \cdot P \cdot g \quad (2)$$

where V_S is the detected voltage signal by the photodiode, $\Delta\lambda_B$ is the Bragg wavelength shift caused by the incoming acoustic wave (due to strain), G is the grating slope (red line in Fig. 2a), R_D is the photodiode response factor, P is the laser input power and g is the gain factor of the PD amplifier. It is worth noting here, that the use of phase- or pi-shifted FBGs

(PSFBGs) can greatly enhance factor G in Eq. (2). In the work of Wu and Okabe [12], the use of a PSFBG resulted in a slope of 87.00 nm^{-1} as compared to a slope of 0.48 nm^{-1} for a standard FBG. This feature significantly improves AE sensitivity, but at the cost of dynamic range (reduction of detectable acoustic range). However, in the ultrasonic regime, the strain applied to the fibre is always small and therefore the reduction of dynamic range is not posing a practical problem. In the work of Wu and Okabe [12], they managed to achieve a frequency response above 1 MHz and a signal to noise ratio (SNR) of 28 dB in the $\approx 300 \text{ kHz}$ frequency range using a PSFBG and balanced PD. The minimum detected sensitivity of this system was estimated to be in the order of $\varepsilon_{min} = 9 \text{ n}\varepsilon/\text{Hz}^{1/2}$.

In the present work, we demonstrate the use of FBGs and PSFBGs as AE sensors for laser processing. Actually, we will classify the laser power based on the AE signals acquired from the sample that the laser power can be related to the sample quality. The signals from the fibre sensor were analysed by wavelet decomposition and then classified by random decision forest [13]. The efficiency of this approach was already reported in our previous work [14]. The sensitivity of in-house produced fibre sensors was compared to the standard piezoelectric sensors.

Experimental setup

An industrial fibre-coupled laser system Starfiber 150/300P (Coherent, Switzerland) was used for welding. Details of the system can be found elsewhere [14-15]. Single laser pulse experiments were performed on a 2 mm thick TiAl4V6 plates (Titanium Grade 5). The pulse duration were kept constant at 5 ms. The laser powers were chosen to provoke different quality. The selected laser powers were 20, 40, 80, 120 and 250 W. After each pulse, the sample was moved by a distance of 0.4 mm to ensure a fresh surface for the following pulse. Thirty five pulses for each laser power condition were made and the corresponding AE signals were used for training of the machine learning classifier.

For the acoustic emission detection, a setup similar to the one in Fig.1 was used. A tunable laser with 100 kHz linewidth (Yenista TLS WDM) was set at the slope of either a uniform, top-hat profile FBG, or that of a phase-shifted FBG (both custom made, in-house using the phase mask technique). At the laser exit, a $> 40 \text{ dB}$ isolator was used to prevent light back-reflections interference. In addition, a 1:2 coupler routed the signal to the sensing arm (FBG or PSFBG) and from there to the photodiode (PD) or balanced PD. The optical fibres were glued on the bottom of the sample holder using the adhesive Loctite HY 4070 (Henkel, Switzerland) and this is illustrated in Fig. 3. At an equal distance from the weld point, a piezoelectric sensor PICO (Physical Acoustics (PAC), USA), sensitive within the range 200 – 750 kHz, was placed. It was fixed on the weld sample with a clamp to ensure good contact as shown in Fig. 3. The signals from all sensors were acquired with a Vallen acquisition unit (Vallen GmbH, Germany) at a fixed sampling rate of 10 MHz.

Wavelet sonograms were constructed from the acquire signals using wavelet decomposition with Daubechies mother wavelet with ten vanishing moments [16]. The obtained sonograms were fed to the machine learning framework to find the unique acoustic signatures of different power regimes. Among the 35 signals for each power, 25 were used to train the algorithm and the remaining 10 for tests.

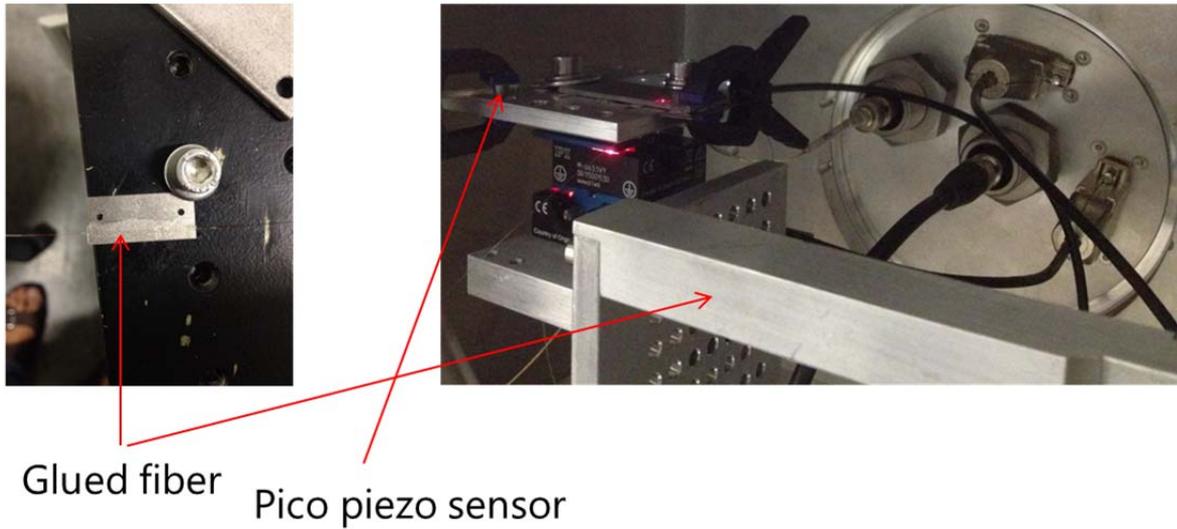


Fig. 3. Picture of the setup inside an atmospheric chamber. On the left, the bounded FBG. On the left the PICO piezo sensor and the location of the bounded fibre.

Experimental results

To start with, the raw AE signals obtained using the uniform, top-hat profile FBG are presented in Fig. 4. In this case, a simple photodiode was used to acquire the data, thus no noise intensity filtering took place in the opto-acoustic setup. Also in Fig.4, the FBG raw AE signals are compared to the standard piezoelectric system for 3 different average weld powers (20, 80 and 250 W) during a 5 ms laser pulse.

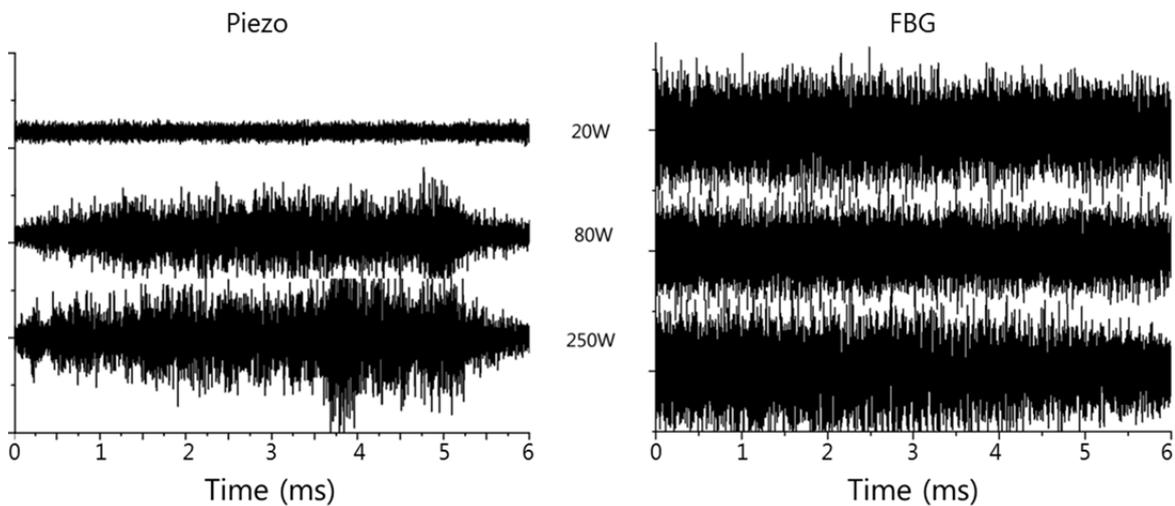


Fig. 4. Response of piezoelectric (left) and edge filter FBG sensor to the acoustic wave generated for 20, 80 and 250 W average power laser weld in TiAl4V6 plates (Titanium Grade 5).

In this first set of measurements, obviously, the piezo AE sensor performs better with a clear ultrasonic signal detection (mostly in the 50 - 400 kHz range) while the unbalanced, uniform FBG contains noisy data. The classification accuracy using the AE raw signals of the two sensors in the machine learning framework are presented in Table 1. In this table, the laser power (related to the sample quality) (in rows) versus the ground truth (in columns) are given. The classification accuracies in the table are defined as the number of true positives divided by the total number of tests for each category. These values are given in the diagonal cells of the table (grey cells). The classification errors are

computed as the number of the true negatives divided by the total number of the tests for each category. These corresponding values are filled in non-diagonal row cells. For example, for the PICO Piezo acoustic sensor, the laser power of 120 W was classified with an accuracy rate of 60% and so it has the highest error rate for this sensor. The classification error is split between 80 and 250 W, 10 and 20%, respectively. Based on Table 1, the classification accuracy favours the use of piezoelectric sensors.

Table 1. Laser welding classification results after AE detection using piezoelectric and uniform FBG sensors. The laser power (20, 40, 80, 120 and 250) are given in [W] in both axes.

PICO Piezo acoustic sensor						FBG acoustic sensor				
Ground truth \ Test categories	20	40	80	120	250	20	40	80	120	250
20 W	100					70	30			
40 W		100				20	70	10		
80 W			80	20			20	60	20	
120 W			10	60	30			30	60	10
250 W					100				30	70

In this specific case, the underperformance of the FBG based sensor setup has a three-fold origin. First, the back-reflection of the FBG is directly coupled to a single photodiode, thus, including the laser intensity and phase noise. These two sources of noise, especially in the laser intensity, account for a large DC component of the output voltage, increasing the signal to noise ratio (SNR) by orders of magnitude. Second, the spectral profile of a typical uniform, top-hat profile FBG is not steep enough for adequate AE detection in the ultrasonic range and, therefore, the use of a spectrally steeper FBG, like a PSFBG would be required for a larger SNR. Finally, the mounting of the FBG to the metal sample holder can have an important effect on the AE signal coupling to the fibre due to the significant acoustic impedance mismatch between the materials. It is important to mention that none of these factors were optimized in our experiments.

In an attempt to overcome some of these limitations, imposed by standard FBG, a 1.5 mm long phase-shifted FBG was produced in-house in a standard 125 μm optical fibre as well as in 80 μm photosensitive SM1500 optical fibres (Fibercore Ltd, USA). The performance of the PSFBG was tested using the standard ASTM E976 test [17] for AE detection of a pencil lead break. The waveform acquired by a simple uniform FBG and the PSFBG is presented in Fig. 5.

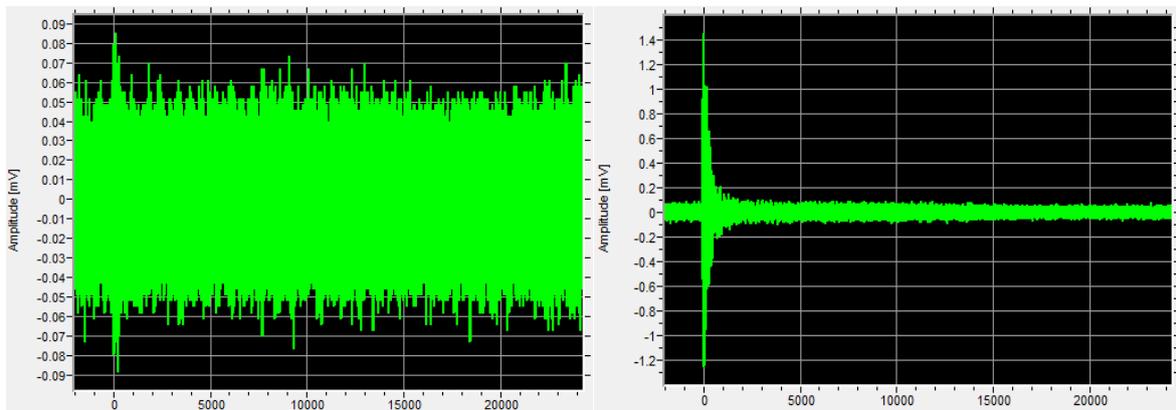


Fig. 5. Response of uniform FBG (left) and PSFBG (right) to the AE of a pencil lead break. An 11dB increase in the SNR is observed by using the PSFBG. Time scale in x-axis is in μs .

Calculation of the signal to noise ratio for the two FBGs reveals an increase of 11 dB for the case of PSFBG detection as compared to the normal, uniform FBG, which is in close agreement to the findings of Wu and Okabe [12], where the gain in SNR was in the order of 14 dB. The result can be further optimized by using of a balanced photodetector

with equal weights on both ports. That would require a PSFBG with at least 50% reflectivity which was not the case for our in-house made PSFBG. Using the PSFBG sensor with the current setup, acoustic frequencies up to 500 kHz were detected, similar to the response of the PICO piezo sensor.

Future work is directed towards the optimization of the sensing element itself, its mounting, as well as setup improvements. Regarding the optimization of the sensing element, as the FBGs are produced in-house, precisely engineered phase-shift FBGs are scheduled to be produced in both standard (125 μm) and small diameter (80 μm) optical fibres. By doing so, the response of the sensor is expected to increase by improving the G factor in Eq. (2) (increase of the slope), as well as increasing the induced $\Delta\lambda_B$ for the same actuation amplitude which is caused by the smaller mass of the smaller diameter of the optical fibre. Concerning the mounting, location, orientation and placement of the optical fibre, several fibre orientations and placement methods as well as holder designs are under investigation. The performance of an airborne detection scheme (fibre not attached directly to the AE plate) was recently tested and the preliminary results are shown in Fig. 6. They exhibit successful functionality with similar bandwidth as compared to a normal microphone.

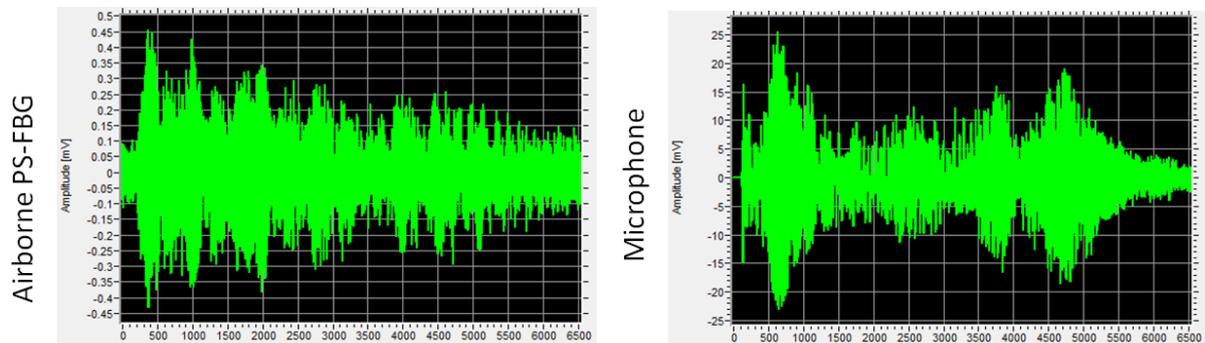


Fig. 6. Airborne PSFBG waveform versus a microphone during a 5 ms duration laser welding experiment. Time scale in the x-axis is in μs .

Finally, the use of 50:50 balanced detection scheme on the setup is expected to improve the SNR by an additional 3 dB and low pass filtering is to be used to exclude noise from ambient conditions (air flows, temperature, etc.), further enhancing the fibre functionality.

Conclusions

In this work, standard piezo acoustic sensors were compared to several optical fibre based. We could also conclude that the use of FBG-based AE detection system for laser processing applications in conjunction with machine learning algorithms for classification tasks has been demonstrated. The experiments showed that, with a non-optimized setup, the uniform, top-hat profile FBG (most basic system) is more subjected to noise as compared to the piezo technology. Under these circumstances, the system in its most basic form, i.e. unbalanced photodetection using a normal uniform FBG, is underperforming compared to commercially available piezoelectric sensors, despite its ability to detect in the ultrasonic range. However, early results on the use of phase-shifted FBGs along with balanced photodetection showed the very promising results. By improving also the mounting, location, orientation and placement of the optical fibre in conjunction with new holder designs, we expect that opto-acoustic sensors either match and/or out-perform traditional piezo-based AE systems, with a smaller footprint, higher flexibility and expandability package with next to zero maintenance needs.

References

- [1] A. Cusano, A. Cutolo, and J. Albert, "Fibre Bragg grating sensors: recent advancements, industrial applications and market exploitation". Bentham Science Publishers, 2011, doi: [10.2174/97816080508401110101](https://doi.org/10.2174/97816080508401110101).
- [2] R. Kashyap, "Fiber bragg gratings", 2nd edition, Academic press, 2010, doi: [10.1016/C2009-0-16830-7](https://doi.org/10.1016/C2009-0-16830-7).
- [3] W. Graham, and S. Hinckley, "Acousto-ultrasonic optical fibre sensors: overview and state-of-the-art." IEEE Sensors Journal Vol 8(7), pp: 1184-1193, 2008, doi: [10.1109/JSEN.2008.926894](https://doi.org/10.1109/JSEN.2008.926894)
- [4] J.A. Bucaro, H. D. Dardy, and E. F. Carome, "Optical fiber acoustic sensor", Applied optics, Vol. 16(7), pp: 1761-1762, 1977, doi: [10.1364/AO.16.001761](https://doi.org/10.1364/AO.16.001761).
- [5] J. A. Bucaro and E. F. Carome, "Single fiber interferometric acoustic sensor" Applied optics Vol. 17(3) p: 330-331, 1978, doi: [10.1364/AO.17.000330](https://doi.org/10.1364/AO.17.000330).
- [6] D.J. Webb, J. Surowiec, M. Sweeney, D. A. Jackson, L. R. Gavrilov, J. W. Hand, L. Zhang, and I. Bennion, "Miniature fibre optic ultrasonic probe" Proceedings Volume 2839, Fibre Optic and Laser Sensors XIV; 1996, doi: [10.1117/12.255383](https://doi.org/10.1117/12.255383).
- [7] D. Gatti, G. Galzerano, D. Janner, S. Longhi, and P. Laporta "Fibre strain sensor based on a π -phase-shifted Bragg grating and the Pound-Drever-Hall technique" Optics express Vol. 16(3), pp: 1945-1950, 2008, doi: [10.1364/OE.16.001945](https://doi.org/10.1364/OE.16.001945).
- [8] M. Takuma, S. Hisada, K. Saitoh, Y. Takahashi, Y. Kobayashi, A. Kadono, A. Murata, S. Iwata, and T. Sasaki, "Acoustic emission measurement by fibre Bragg grating glued to cylindrical sensor holder" Advances Materials Science and Engineering, Article ID ID 274071, 12 pages, 2014, doi: [10.1155/2014/274071](https://doi.org/10.1155/2014/274071).
- [9] N. Takahashi, K. Tetsumura, K. Imamura, and S. Takahashi, "Fibre Bragg grating WDM underwater acoustic sensor with directivity" Proceedings Volume 3541, Fibre Optic and Laser Sensors and Applications; Including Distributed and Multiplexed Fibre Optic Sensors VII; (1999, doi: [10.1117/12.339083](https://doi.org/10.1117/12.339083).
- [10] N. E. Fisher, D. J. Webb, C. N. Pannell, D. A. Jackson, L. R. Gavrilov, J. W. Hand, L. Zhang, and I. Bennion, "Ultrasonic hydrophone based on short in-fibre Bragg gratings" Applied optics, Vol. 37(34), pp: 8120-8128, 1998, doi: [10.1364/AO.37.008120](https://doi.org/10.1364/AO.37.008120).
- [11] W. Graham, and S. Hinckley, "A transmit reflect detection system for fibre Bragg grating acoustic emission and transmission sensors" Smart Sensors and Sensing Technology, Vol. 20, pp: 183-197, 2008, doi: [10.1007/978-3-540-79590-2_13](https://doi.org/10.1007/978-3-540-79590-2_13).
- [12] Qi Wu, and Yoji Okabe, "High-sensitivity ultrasonic phase-shifted fiber Bragg grating balanced sensing system" Optics express Vol. 20(27), pp: 28353-28362, 2012, doi: [10.1364/OE.20.028353](https://doi.org/10.1364/OE.20.028353).
- [13] L. Breiman, "Random forests", Machine Learning, Vol. 45(1), pp: 5-32, 2001, doi: [10.1023/A:1010933404324](https://doi.org/10.1023/A:1010933404324).
- [14] S. Shevchik, T. Le-Quang, B. Meylan and K. Wasmer, "Acoustic emission for in situ monitoring of laser processing", 33rd European Conference on Acoustic Emission Testing (EWGAE 2018), downloadable at: ewgae2018/papers/35.pdf.
- [15] Q. T. Le, S. Shevchik, B. Meylan, F. V. Farahani, M. P. Olbinado, A. Rack, K. Wasmer, "Why is in-situ quality control of laser keyhole welding a real challenge?" Procedia CRIP (2018), doi: [10.1016/j.procir.2018.08.055](https://doi.org/10.1016/j.procir.2018.08.055).
- [16] I. Daubechies, "Ten Lectures on Wavelets"; CBMS-NSF Lecture Notes Nr. 61, SIAM, 1992, doi: [10.1137/1.9781611970104](https://doi.org/10.1137/1.9781611970104).
- [17] ASTM Standard E976-15, "Standard guide for determining the reproducibility of acoustic emission sensor response". ASTM, Philadelphia, 2015, doi: [10.1520/E0976-15](https://doi.org/10.1520/E0976-15).