Novel technique for distributed fibre sensing based on faint long gratings (FLOGs)

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ABSTRACT

A novel approach for fibre distributed sensing is proposed, conceived to match as closely as possible to an ideally responding distributed sensor. It is demonstrated that it can be actually realized using fibre Bragg gratings of extremely low index contrast and continuously printed over the entire fibre length. The concept is experimentally validated over a restricted distance range that proves the huge potentialities of the technique in terms of response and precision.

Keywords: optical fibre sensor, distributed fibre sensor, fibre Bragg grating, optical reflectometry

INTRODUCTION AND MOTIVATION

Distributed optical fibre sensing techniques have gained a sustained interest during the past decade and has gradually turned into a mature technology, showing growth rates in terms of economic return and technical development outperforming all other classes of fibre sensors. Today there are clearly 2 types of distributed fibre sensing techniques that show higher profiles in terms of potentiality and sensing performance, namely the sensors based on stimulated Brillouin scattering (BOTDA/BOFDA)[1,2] and those based on coherent Rayleigh backscattering (C-OTDR/C-OFDR)[3]. Without neglecting the importance of other distributed sensor technologies, such as those based on spontaneous Raman scattering, only these 2 types of sensors have clearly shown a continuing significant progress during the recent period.

These 2 types of sensor share a common crucial advantage: they can be implemented using the most standard and simple single mode fibres, without sensitizing processing during fabrication. However, as clarified hereafter, they both suffer from intrinsic penalties in term of power efficiency and quality of the response. Such an analysis has not been really performed so far, to our knowledge, and the important issues to keep in mind are the following:

- **Brillouin sensors**: the principle is based on the dynamic generation of Bragg gratings, by the resonant generation of an acoustic wave. The physical process is optically nonlinear, so that a substantial power is required to just generate a very weak grating, but the power taken from the activation signal – the pump pulse – is entirely coupled to the response signal. Since the grating is dynamically generated, its phase and pitch are automatically adapted when the refractive index varies, e.g. under the effect of temperature and strain. It means that its response to refractive index changes is very minor, so that its sensitivity is essentially given by the dependence of the acoustic velocity on temperature and strain. This dependence is 1000X smaller in term of resonance shift than the comparable effect of the refractive index on a Bragg grating. Brillouin sensors can deliver an absolute value of the measured quantity.

- **Coherent Rayleigh sensors**: they are based on the continuous natural isotropic scattering, originating from small stochastic fluctuations in the refractive index along the fibre. The process can be locally modelled as a very weak fibre Bragg grating (FBG) with random amplitude and pitch. It is permanently frozen in the fibre during fabrication, so that no energy is actually needed to generate the grating that can be interrogated by a simple linear reflection. The efficiency of the process is nevertheless very low, since only a minor fraction of the isotropically scattered light is re-captured in the backwards direction, typically ~0.15% in a single mode fibre. The backscattered wave shows strong random but stationary intensity fluctuations that contains the information about these frozen stochastic refractive index variations. Any variation of the refractive index under environmental changes (temperature or strain) will modify the random intensity pattern of the backscattered light and the amount of change can be retrieved by changing the laser wavelength to compensate the phase shift due to the optical path change. The proper

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wavelength change is determined by the maximum correlation between intensity traces at the original and the tentative new wavelength. The full sensitivity to refractive index changes is observed, but only relative measurements of the environmental quantities can be performed.

A system combining the advantages of the 2 techniques would undoubtedly be a crucial progress and certainly lead to a massive boost of the performance. A synthesis of this analysis shows that the ideal distributed fibre sensing technique would require no energy to create the spectrally selective distributed reflection, like in coherent Rayleigh systems, with a full sensitivity to refractive index changes, also like in coherent Rayleigh systems, and with a 100% return of the reflected pump light to the response, like in Brillouin systems, and delivering absolute measurements of the environmental quantity, also like in Brillouin systems. Such an ideal system turns out to be impossible using a simple unprocessed fibre, but exists using a mature fibre preparation technique: the fibre Bragg grating (FBG). This lossless fibre element has demonstrated its huge potentiality to realize highly sensitive point sensors.

To turn FBGs into a building block for distributed fibre sensing, this would require the printing of the FBG all along the sensing fibre. What looks like a simple conceptual extension of an existing technique actually turns into an entirely new paradigm, since the conditions to be fulfilled for distributed measurements turn out to be entirely different, even opposite to the ones prevailing for conventional FBG point sensors. As will be demonstrated in this paper, it is essential to realize continuous FBG with no phase hopping – immediately disqualifying the simple solution consisting in closely appending discrete FBGs all along the fibre – and with extremely low index contrast to maintain a low reflection per unit length. For long distance sensing the contrast must be even lower than the random index fluctuations giving rise to Rayleigh scattering, so that it sounds reasonable to designate such an element as a *faint long grating* (FLOG).

In this paper we present the basic principles behind the conception and operation of a FLOG distributed sensor. This leads to the conditions to be realized in term of index contrast and to the prediction of the potential sensing range. Since FLOGs do not currently exist and have not yet been demonstrated, this analysis may sound vain at first glance. But nothing practically prevents the realization of such faint gratings, since it may look as a simple downgrade of existing techniques and the focus of concern has been so far placed on maximising the index contrast in FBGs. The proof-of-concept of the technique is experimentally demonstrated in this paper over a restricted distance.

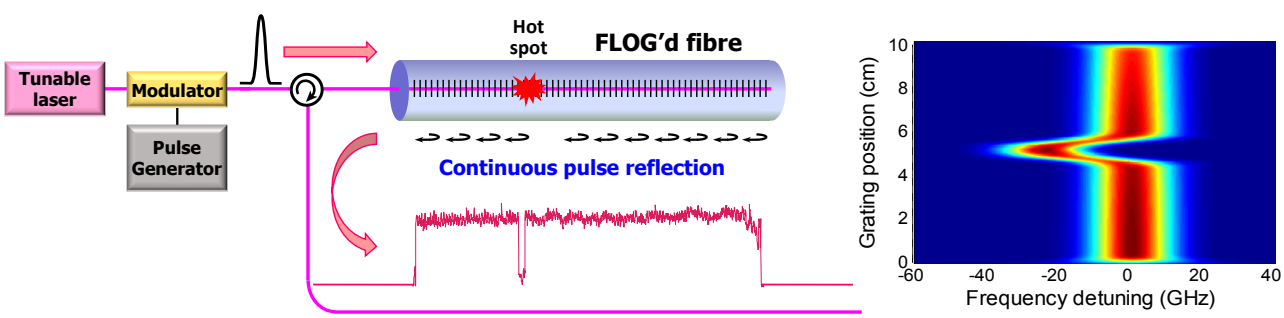

Figure 1. Schematic diagram of a generic FLOG distributed fibre sensor. On the right, 3D graphical representation of the intensity map obtained when the laser frequency is scanned, showing the distributed reflection spectrum (simulation of real conditions).

DESCRIPTION AND PRINCIPLE

The operation of the sensor is quite straightforward and its implementation using optical time-domain reflectrometry is depicted in Fig. 1. Since the system response is linear, frequency-domain implementations are also possible and will be considered as an equivalent dual configuration. The basic elements are a laser source, in which the light frequency can be finely and reproducibly tuned like in BOTDA or C-OTDR systems, a pulse shaping modulator and a circulator. At a given frequency a trace of the reflected signal from the propagating laser pulse is recorded in the time domain, delivering a distribution map of the FLOG reflectivity along the fibre. This operation is repeated by scanning the laser frequency over a given range, so that a position-resolved reflectivity spectrum of the FLOG can be retrieved, as shown in Fig. 1 right. Just like in BOTDA systems the frequency of the peak reflectivity can be determined by fitting the local reflectivity spectrum. This frequency corresponds to the local Bragg resonance that may be shifted in presence of local environmental changes, like illustrated in Fig. 1 for a hot spot.

The spatial resolution is determined by the pulse duration like in any optical time-domain reflectometers. Considering the very long length of the FLOG, the global reflection spectrum is extremely narrow if the fibre is uniform. However,

the effective reflection length of the grating can be considered in a first approach as the portion of the grating covered by the light pulse, so actually a length equal to the spatial resolution. This shows an immediate benefit of the technique: spatial and frequency resolutions are related by an uncertainty relation and the system is thus naturally Fourier-transform limited. In the case of a Gaussian pulse, the FWHM spectral width $\Delta\nu$ of the reflected power spectra is related to the FWHM pulse width T in intensity by the relation:

$$T \times \Delta\nu = 2\ln 2 / \pi = 0.441 \quad (1)$$

An estimation with simple figures can be entered here: the pulse width for a 1 m spatial resolution is $T = 10$ ns, so that the width of the reflected spectra is $\Delta\nu = 44.1$ MHz. Considering that in BOTDA systems the central frequency can be determined with a precision of 1/30 of the resonance width, by analogy the accuracy on the determination of the local Bragg frequency should be 1.5 MHz. Using the well-known dependence of Bragg frequency shift as a function of temperature of about 1.3 GHz/K, it shows that a tremendous precision of 1 mK can be potentially obtained. It also means that a 1 K temperature accuracy is secured down to a 1 mm spatial resolution.

It is also essential to evaluate the potential distance range of such a distributed sensing system. Actually the reflectivity of the weak FBG must be contained between 2 limits: if the grating shows a too high reflectivity, the interrogating pulse will be severely depleted before reaching the distant end of the FLOG and the measurement will be no longer possible. Reversely, if the reflectivity is too low, natural backscattering processes will dominate the distributed reflection signal from the FLOG. Inspired by the similarity of the depletion impact in Brillouin sensors[4], it can be deduced that, in the worst case, the bias in the determination of the peak reflection frequency is smaller than 1.5% of the FWHM spectral width if the extra loss due to the grating reflectivity is smaller than 20%. This actually corresponds to the integrated reflection loss experienced by the pulse during its propagation over the entire fibre length L.

Using the standard coupled-wave model for a weak FBG, it can be straightforwardly deduced that such a total reflectivity is reached if the product

$$\textit{linear reflectivity} \times \textit{grating length} = 0.96 \quad (2)$$

Here linear reflectivity means amount of reflection per unit length for an infinitesimal distance increment and is directly proportional to the grating index contrast. Since all interactions are linear, it must be mentioned that, for very long fibres in which the cumulated effect of linear loss is important and even dominating, this expression is still valid by correcting and re-scaling the numerical factor with the total attenuation, as can be rigorously demonstrated.

By comparing with the strongest backscattering process in optical fibers, i.e. Rayleigh scattering, equivalent to a linear reflectivity of 5×10^{-8} m^{-1} at 1550 nm, a FLOG with equal linear reflectivity can still perform measurements with less than 20% total depletion up to a distance of 19'000 km! Of course this range is totally unrealistic for reasons extrinsic to the sensor principle, namely natural linear loss. However, reversely, it can be straightforwardly calculated that a 100 km long FLOG with less than 20% pulse depletion will give a comfortable reflection signal 33 dB larger than Rayleigh backscattering. The reflection traces can certainly be obtained with minor averaging at metric spatial resolution.

But this 100 km grating must be weak enough to show a total reflectivity smaller than 20%, which is technically extremely challenging. It can be easily calculated that, for distance ranges longer than 5 km, the required index contrast must be smaller than the stochastic index fluctuations, frozen during fibre solidification and at the origin of Rayleigh scattering. The purpose of the demonstration is just to show that there is no fundamental limitation to make kilometer-long sensors using FLOGs, i.e. with a distance range comparable to other distributed fibre sensing techniques and with the possibility to still get a comfortable reflection signal. The challenge is now to find a solution to produce extremely long, ideally uniform, FBG showing a very low reflectivity and some recent results demonstrate possible approaches[5].

EXPERIMENTAL DEMONSTRATION

The experimental validation of the concept of FLOG distributed sensing has been carried out using the longest possible grating that could be home fabricated: a 10-cm long FBG with the weakest contrast delivered by the printing system. The optical properties of the FBG are measured using a broadband light source, showing an overall reflectivity of 35% and a central wavelength at 1549 nm. It means that, despite our efforts, the index contrast and thus the linear reflectivity is slightly too large, since the total reflectivity is in excess of the 20% safe value. A commercial distributed-feedback (DFB) laser diode is used as a light source. Its output is connected to an external fast electro-optic modulator (EOM) followed by a nonlinear fibre loop mirror, so that its intensity could be shaped as a Gaussian pulse with 20 ps FWHM duration. The spectral distribution of the FBG reflection can therefore be measured with a 2 mm spatial resolution[6].

To conveniently measure the variation of the Bragg frequency along the weak FBG, the laser frequency was precisely tuned by controlling the injection current applied to the laser diode. Then the pulse reflection was monitored by scanning step-by-step the central frequency of the signal pulse, by 250 MHz increments over a span of 125 GHz. Considering the effective reflection bandwidth of 22 GHz, the reflection spectrum was sampled over 88 points, which gives enough accuracy to determine the peak frequency of the reflected spectrum with a good precision[7]. The time waveform at each step was acquired without averaging using a sampling oscilloscope with a 80 GHz optical module, proving the ideal response efficiency of the technique.

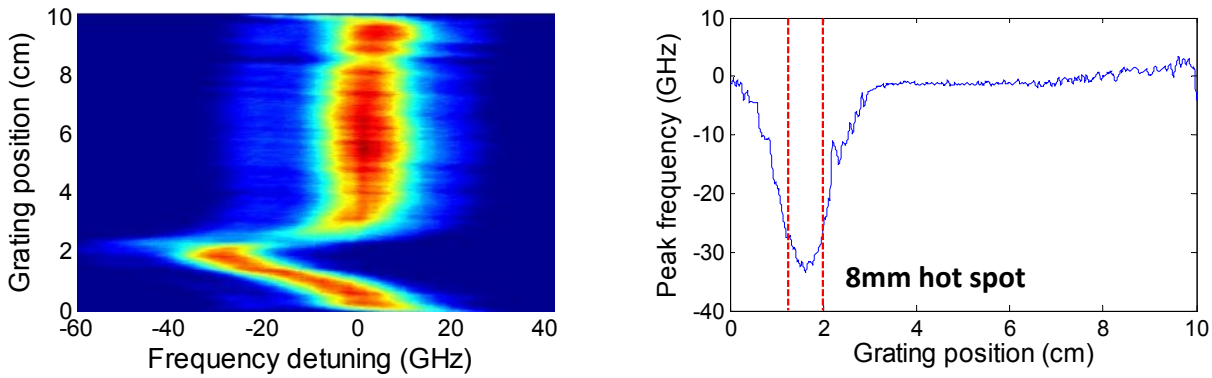

Fig. 2. Left: 3D plot of the distributed reflection spectrum of a 10 cm weak fibre grating. A 8 mm hot spot is positioned at 2 cm from the grating input. Right: Corresponding estimated frequency of the peak reflectivity as a function of distance.

The obtained distributed reflection spectra are plotted in Fig. 2, obtained with no averaging, demonstrating that an 8 mm hot spot can be sharply resolved. The accuracy on the determination of the peak reflectivity frequency is experimentally determined to be 320 MHz, which corresponds to a temperature accuracy of 0.3 K, in safe agreement with the theoretical predictions for a 2 mm spatial resolution.

This practically demonstrates that FLOG systems can potentially massively outperform existing distributed fiber sensing solutions, in terms of accuracy and response signal, that will globally upscale performance. This is subject to the condition that a technological solution can be implemented to fabricate FLOGs in a mass production approach, which will require sustained efforts but does not belong to technical utopia. According to predictions the potentialities of such a distributed sensing technique are absolutely tremendous and, if the fabrication of FLOGs can be routinely demonstrated, it should be clearly a revolution in the field.

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