30cm of spatial resolution using pre-excitation pulse BOTDA technique

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ABSTRACT

A pre-excitation pulse technique in Brillouin optical time domain analysis (PP-BOTDA) for enhancement of the spatial resolution is shown. The technique here exposed is based on the pre-excitation of the stimulated Brillouin scattering and the subtraction of the Brillouin scattering due to the intensity dc level present in the optical pulse. A main optical pulse with 3ns of duration followed by a pulse of 40ns and half the intensity of the main one are used for obtaining 30cm of spatial resolution. The spatial range is 3600m on a standard single mode optical fiber.

Keywords: Optical fiber sensors, distributed measurement, stimulated Brillouin scattering.

1. INTRODUCTION

Distributed Brillouin sensing in optical fibers is commonly obtained by using a pump pulsed light and a continuous shifted probe signal. The intensity of the probe field is measured as a function of the frequency shift to resolve the Brillouin gain spectrum (BGS). The information of the probe is located on the fiber through a time-domain analysis; the shorter the pump pulse the better the spatial resolution. However, the Brillouin gain spectral width broadens as the pump pulse is reduced [1]. Thus, determining the resonant Brillouin shift is more difficult and therefore measurements of submeter defects on the fiber are obtained with a larger error. In spite of this drawback in the Brillouin sensing, many works to improve the spatial resolution have been reported. Among these works there are some interesting approaches.

An interesting approach is based on the preexistence of a non negligible acoustic wave along the fiber that matches the Brillouin frequency of the medium. This acoustic wave is typically obtained by stimulated Brillouin scattering and it has a lower response (~10ns) to variations of amplitude and phase than the probe and pump optical waves. Then, rapid variations of amplitude and phase of the pump within the duration of the acoustic wave can induce fast changes of the steady state amplification of the probe, which are fully observable with a BOTDA system. This situation can be obtained when the light is pulsed by a device with a low extinction ratio, since it allows the presence of an optical intensity dc level. Such is the case of an electro optic modulator (EOM) with extinction ration about 20dB [2]; some centimeter spatial resolution at hundred of meters of spatial range are reported for standard optical fibers [3]. Other ways to have the preexistence of the acoustic wave are: the dark pulse technique [4] and the π-phase pulse [5]. Nevertheless, in these techniques the acoustic wave partially decays during the pulse duration, and a second attenuated response appears beyond the acoustic life time that hides the measurement of submeter perturbations on the fiber. One solution to suppress or attenuate the impact of this background Brillouin response is based on subtraction of two BGS. e.g., the subtraction of two BGS traces obtained from pulses shift in time or pulse with different widths [6]; in this technique the rising and the falling times of the pulses define the spatial resolution.

In this paper, a combination of a controlled optical intensity before the main pulse, and a subtraction of the background Brillouin backscattering is proposed and experimentally checked. A true spatial resolution of 30cm in 3600m of standard single mode optical fiber (SMF) is measured in the laboratory.

2. PRINCIPLE

In BOTDA technique the pulse of light determines the spatial resolution of the distributed sensor; the longer the pulse the narrower the BGS width and more gain in the Stokes signal. However, the constraint imposed by the dumping time of the acoustic wave fixes the lower limit of light pulse duration. A proper pulse of light for BOTDA systems should

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have the shape depicted in Fig. 1.a (upper figure) with no optical intensity remaining; nonetheless devices used for modulating the signal, e.g. an EOM, allow the presence of a non-zero optical intensity (δI) after and before the duration of the pulse. The quantity of such intensity can be given by the extinction ratio of the switching light device. Hence, the dc level influences the final performance of the BOTDA system for a pulse shorter than 10ns, and also induces the appearance of a background Brillouin response.

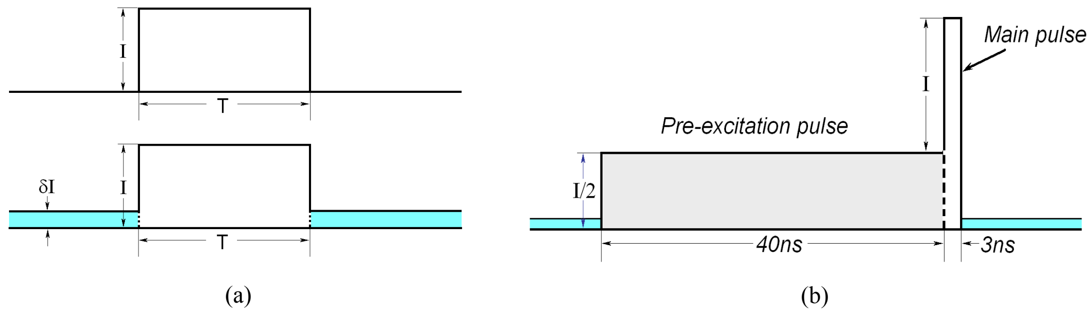


Fig. 1. Optical pulse with (upper) and without (lower) zero pulse base (a). Optical pulse with non zero pulse base, pre-excitation pulse (P-pulse) and main pulse of 3ns. (b)

The continuous non-zero pulse base can be controlled and used for enhancing the submeter Brillouin measurement. Even more, this dc level can also be pulsed and used as a pre-excitation optical field for inducing the acoustic wave that resonates with the Brillouin signal. The pre-excitation pulse can be larger than 20ns, and immediately followed by a shorter pulse with higher intensity than the P-pulse. Thus these rapid variations in the amplitude and phase of the pump can induce fast changes of the steady state amplification of the probe (or Stokes wave), provided that they are within the phonon lifetime (acoustic wave). Additionally to the pre-excitation pulse, the Brillouin due to the pulse base and the pre-exciting pulse is subtracted by obtaining the BGS with and without the main pulse (short pulse). This technique is hereafter called pre-excitation pulse Brillouin optical time domain analysis technique (PP-BOTDA).

3. EXPERIMENTS

The pre-excitation pulse technique is proposed to be used with a typical Brillouin optical time domain analysis system, which uses two counter-propagating optical waves, a pump pulsed light and a continuous probe wave. In our setup the two optical waves are obtained from the same light source. The light is pulsed with an EOM of 40dB of extinction ration and amplified with an Erbium doped fiber amplifier, while the probe is modulated with a RF signal; thus the probe is swept to measure the frequency value at which it resonates with the acoustic wave. The gain of the probe signal is measured and the time-domain signals are monitored with a high speed photodiode. 2000 averages are taken at each frequency step of the probe signal that is set to 1.5MHz.

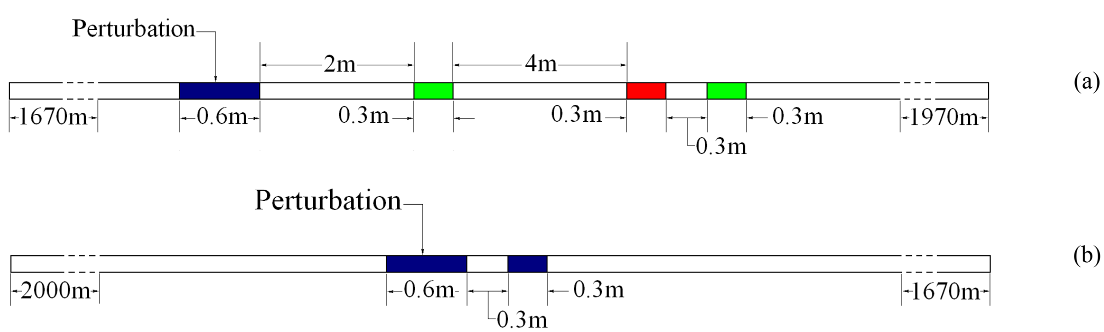


Fig. 2. (a) Emission spectrum of the Brillouin fiber laser ring pumped at 1551nm. (b) Brillouin fiber ring laser gain.

In order to compare the BOTDA and the PP-BOTDA techniques a single mode fiber of 3600m long is used. A first fiber setup includes one perturbation of 60cm and three of 30cm (See Fig. 2.a) placed after 1670m. Fig. 3 summarizes the data obtained with a BOTDA system using two types of pump pulse; one pulse with 5ns of duration (Fig. 3.a), and other of

40ns with half the intensity than the first one (Fig. 3.b). As it can be expected for such BOTDA conditions, the defects are barely detectable and it is not possible to discriminate one from the other. Only the defect of 60cm long is measured with the 5ns pulse; i.e. "the hot spots" larger than 0.5m can be measured; provided that the defect is isolated from other perturbations on the fiber or separated more than 1m.

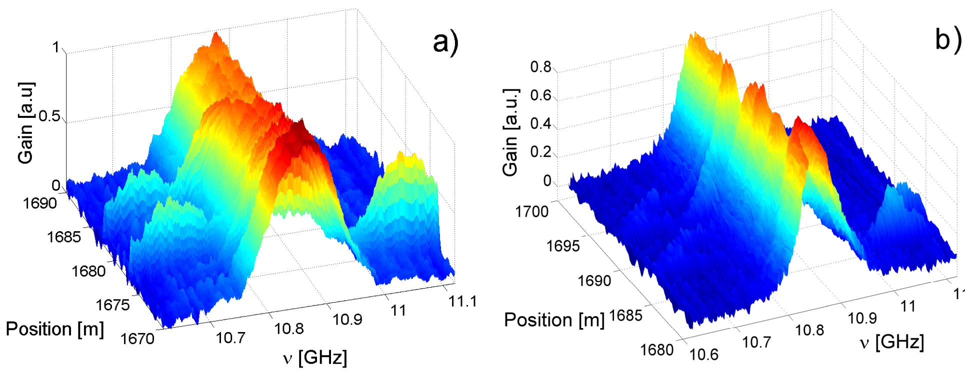
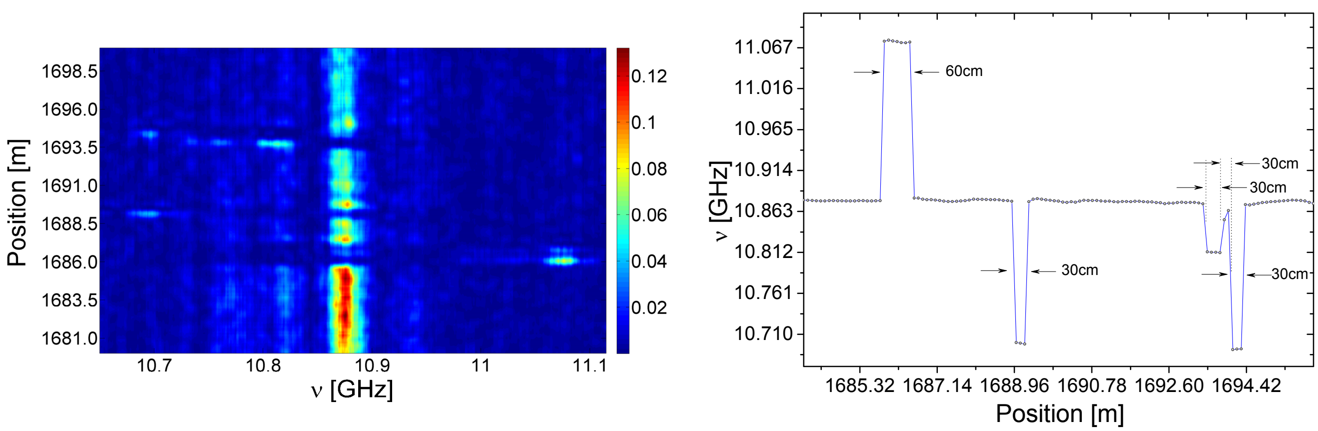


Fig. 3. Brillouin gain spectrum for fiber described in Fig. 2.a using BOTDA with a 5ns pump pulse (a) and a half intensity pump pulse of 40ns (b).

On the other hand, Fig. 4 shows data obtained by using the pre-excitation technique for the fiber described in Fig. 2.a. The pulse used for measuring is depicted in Fig.1.b; it is composed of a pre-excitation base of 40ns and a main pulse of 3ns. The P-pulse has half intensity the main pulse. The perturbations in the fiber are clearly observed and fully discriminated as variations in the Brillouin frequency shift (see Fig. 4.b). We remark the fact that two perturbations of 30cm, which are separated 30cm, are fully detected. This real spatial resolution exposed in the measurements corresponds to the 3ns duration of the main pulse.



(a) (b)

Fig. 4. Brillouin spectrum gain for fiber described in Fig.2.a using PP-BOTDA technique and pulse illustrated in Fig.1.b. (a). Brillouin frequency shift, ν, calculated from the Brillouin spectrum gain (b).

The fiber set of Fig. 2.b is also measured with the PP-BOTDA technique using the P-pulse of Fig. 1.b. The results of Brillouin spectrum distribution are shown in Fig. 5.a. These data are used for calculating the peak value of the BGS, and then map the Brillouin frequency shift along the SMF (Fig. 5.b). These perturbations are located at 2013m from the origin of the fiber that has a total length of 3600m.

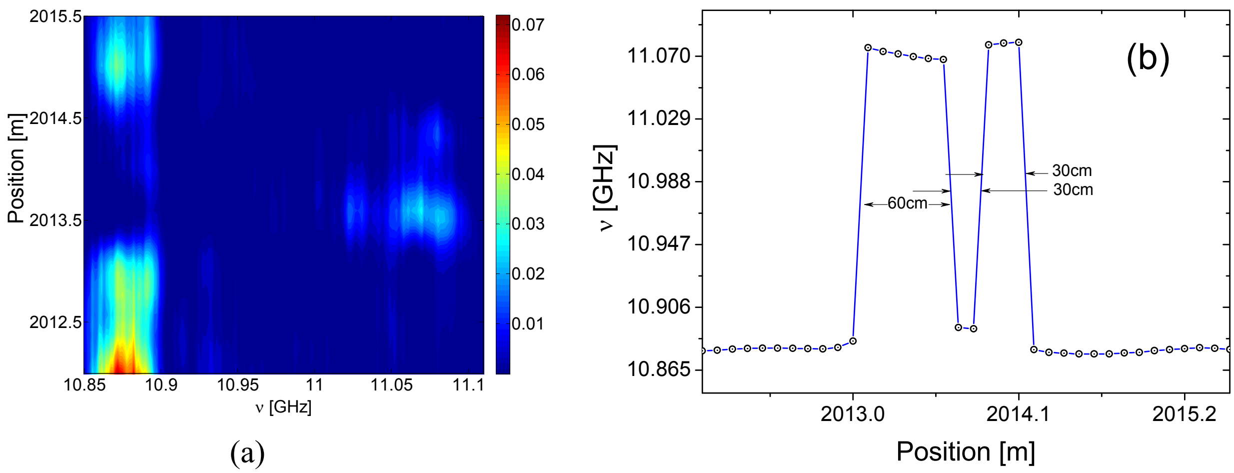


Fig. 5. Brillouin spectrum gain for fiber described in Fig. 2.b (a) and Brillouin frequency shift as a function of position in the fiber of Fig. 2.b for two perturbations of 60cm and 30cm separated 30cm (b).

4. CONCLUSIONS

In this paper, a distributed Brillouin sensing technique (PP-BOTDA) is proposed and experimentally validated. This technique uses a pre-excitation pulse complementarily with a main short pump pulse, in addition to the subtraction of the BGS due to the non-zero pulse base and the pre-exciting pulse. A spatial resolution of 30cm in a spatial range of 3600m is demonstrated with this technique. The method can discriminate perturbations due to strain or temperature on the fiber, which can be of a length equivalent to the main pulse duration and separated at least the same distance. Besides, the PP-BOTDA technique can solve the detection of two defects on the fiber with the same value of frequency shift and separated a distance equivalent to the main pulse duration; i.e. the measurements of these perturbations are not hidden or taken as a unique defect. This technique does not need special optical fibers, and can be used on a relative long spatial range or over short segments of optical fibers. The technique here proposed can be used for measuring static or quasi static perturbations on the fiber; it can also measure dynamic perturbations with a slow variation rate. The results here presented suggest that the PP-BOTDA technique can facilitate the inclusion of the Brillouin sensing in the structural health monitoring (SHM).

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