Zornoza, A., Olier, D., Sagues, M., & Loayssa, A. (2011). Brillouin spectral scanning using the wavelength dependence of the frequency shift. IEEE Sensors Journal. https://doi.org/10.1109/JSEN.2010.2071378

Brillouin Spectral Scanning using the Wavelength Dependence of the Frequency Shift

Ander Zornoza, David Olier, Mikel Sagues and Alayn Loayssa, *Member, IEEE*

***Abstract*— We present a novel Brillouin spectra characterization method based on the Brillouin frequency shift dependence with pump wavelength. It is applied to a Brillouin optical time domain analysis sensor, resulting in a cost-effective experimental setup that also avoids pulse leakage distortion in the measured spectra.**

***Index Terms*— Stimulated Brillouin scattering, distributed fiber sensor, Brillouin fiber sensing.**

I. INTRODUCTION

Brillouin distributed sensing (BDS) relies on the spectral characterization of this nonlinear effect along an optical fiber to measure temperature and strain. This is typically implemented using pump-and-probe schemes in which the wavelength separation of a pump and a probe wave is swept to scan the spectral response of the interaction.

In this letter, we introduce and experimentally demonstrate an alternative spectral scan technique for BDS based on the wavelength dependence of the Brillouin frequency shift. Its main advantage is that it allows the use of a low-cost coarse tunable laser instead of the costly synthesized microwave generators that are deployed in most setups to sweep the pump and probe waves wavelength separation.

II. FUNDAMENTALS AND EXPERIMENTAL SETUP

The wavelength dependence of the Brillouin frequency shift, ν_B, in a singlemode fiber is given by:

$$\nu_B = \frac{2n v_a}{\lambda_p} = \nu_p \cdot \frac{2n v_a}{c} \qquad (1)$$

where n is the modal index at the pump wavelength λ_p, ν_p the optical frequency of the pump and v_a the acoustic velocity. Note that there is an explicit relationship with ν_p, and also another implicit via the wavelength dependence of n. However, the latter can be neglected for most fibers if a small wavelength range is considered.

Fig. 1 highlights how this wavelength dependence of ν_B can be exploited to scan the Brillouin spectra. The basic idea is to change the wavelength of the pump and probe waves simultaneously while their optical frequency difference, f_m, is held constant. ν_B varies with pump wavelength according to (1); thus a different detuning from Brillouin resonance is experienced by the probe wave at each wavelength. This detuning is given by $\Delta\nu = \nu_S - \nu_P + \nu_B$, where ν_S is the optical

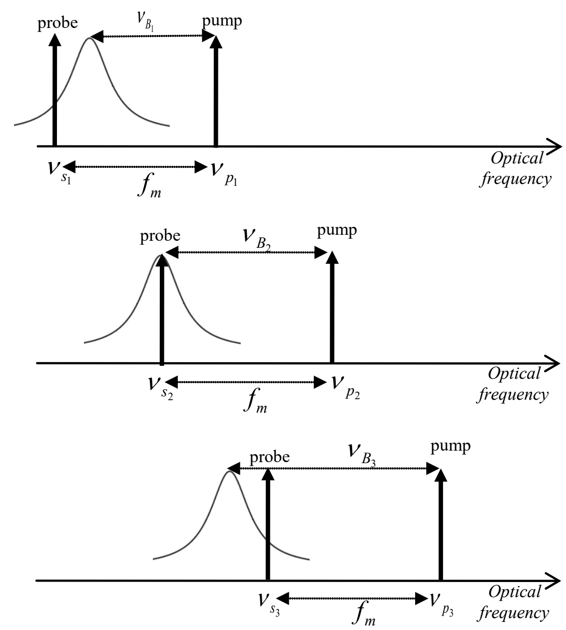


Fig. 1 Fundamentals of the Brillouin spectral scanning method.

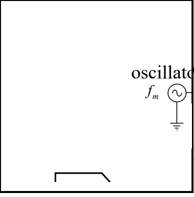
frequency of the stokes wave. In conventional pump and probe $\Delta\nu$ is scanned by modifying (ν_S - ν_p), while in our method it is via ν_B.

A wavelength tunable laser is required to implement this spectral scanning concept. However, typical measured variations of ν_B with pump wavelength in standard singlemode fiber (SSMF) are of the order of 7 MHz/nm at 1550nm [1]. Therefore, fine wavelength tuning is not needed since BDS requires spectrum scanning at around 1-MHz resolution, i.e. 0.15-nm steps. A low-cost wavelength-agile monolithic tunable laser of the type been deployed for wavelength division multiplexing (WDM) networks is sufficient to provide this tuning.

The spectral scanning method that we propose can be applied to BDS operating either in the coherence, frequency or time domains. Here, the latter was implemented. Fig. 2 schematically depicts the Brillouin optical time domain

Manuscript received September 12, 2009. This work was supported in part by the Spanish government through project TEC2007-67987-C02-02.

The authors are with the Universidad Pública de Navarra, Campus Arrosadia, 31006 Pamplona, Spain (e-mail: alayn.loayssa@unavarra.es).



is (BOTDA) setup that we have demonstrated. It is on the sideband generation principle, but using a novel method for pump pulse generation in the RF domain instead of using optical means [2].

The output of a full C-Band tunable laser source is first divided in two branches. High extinction ratio RF pulses are generated using a fixed-frequency microwave oscillator, a baseband pulse generator and a single-pole single-throw

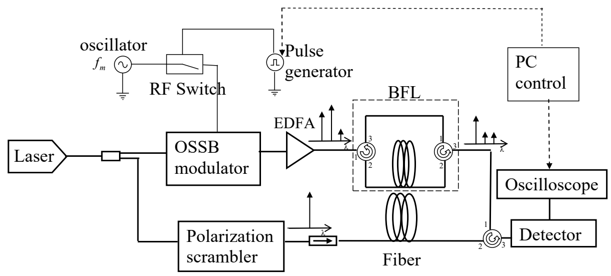


Fig 2: BOTDA experimental setup that performs wavelength Brillouin spectral scanning

microwave switch [2]. Then, the RF pulse shape is directly translated to the optical domain by the use of an optical single-sideband modulator (OSSB). Finally, after amplification with an Erbium doped fiber amplifier (EDFA), a Brillouin fiber laser (BFL) suppresses the optical carrier [3] so that we end up applying a pulsed pump wave with negligible DC base to the sensing fiber. In the lower branch the laser output is directly used to provide the probe wave after polarization scrambling. Finally, the Brillouin spectra distributed along the fibre are measured by tuning the laser wavelength, as it was described above. Note that it is important to choose devices with a negligible wavelength dependence, otherwise their wavelength dependant behaviour should be taken into account.

III. Results and Conclusions

We assembled an experimental setup following the scheme in Fig. 2 for a proof-of-concept demonstration of our system. The only microwave switch that we had available was a model limited to 240ns pulses with 80dB extinction ratio, which set the maximum spatial resolution of the measurements to approximately 24m. However, much faster switches are commercially available so that even sub-meter resolution measurements should be possible with this system.

We performed distributed temperature measurements in a 10-km length of standard single-mode fibre with 200m of fibre placed in a climatic chamber at 42ºC while the rest was at room temperature. Fig. 3 depicts the Brillouin spectra measured along the fibre as the pump wavelength was tuned in 0.13nm steps from 1540.3 nm to 1551.5 nm.

In this type of spectral measurements, the pump wavelength at which the Brillouin gain is maximum gives the strain or the temperature change in the optical fiber. This wavelength is obtained by applying a Lorentzian fit to the distributed measurement of the Brillouin spectra in terms of wavelength. Then, it is necessary to use the dependence of the Brillouin frequency shift on the applied strain $\delta\varepsilon$ and temperature change δT, which can be expressed as [4]:

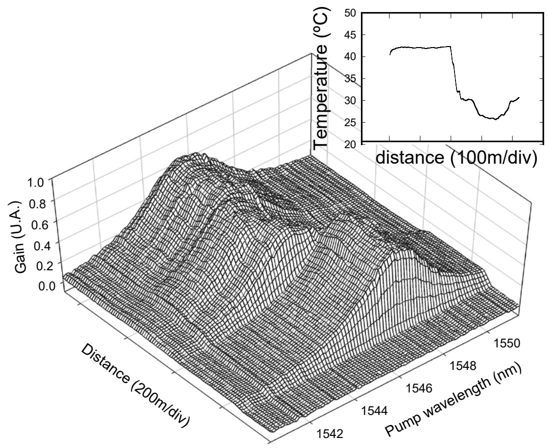


Fig. 3: Distributed measurement of the Brillouin gain for every pump wavelength and the distributed temperature (inset).

$$\nu_B = \left(A'\cdot\delta\varepsilon + B'\cdot\delta T\right)\cdot\nu_{B0} + \nu_{B0} \tag{2}$$

Where ν_{B0} is the Brillouin frequency shift at room temperature and with no strain applied to the fiber, and A' and B' are the normalized strain and temperature coefficients, respectively. In the spectral measurements, at the pump wavelength with maximum gain, $\lambda_{p,\max}$, the Brillouin frequency shift equals the optical frequency difference between pump and probe waves, f_m, which in our setup is set by the microwave oscillator frequency. Therefore we can particularize (3) giving:

$$\nu_B(\nu_{p,\max}) = f_m = \left(A'\cdot\delta\varepsilon + B'\cdot\delta T + 1\right) + \frac{2n\nu_a}{\lambda_{p,\max}} \tag{3}$$

$A' = 4.6648\cdot 10^{-6}\, nm\cdot\mu\varepsilon / MHz$, $B' = 9.8954\cdot 10^{-5}\, nm\cdot{}^{o}C / MHz$, and $2n\nu_a = 16767 nm\cdot MHz$, are obtained from a previous calibration of the fiber under test. Therefore, from (3) we directly calculate $\delta\varepsilon$ or δT. The inset of Fig. 3 depicts the distributed temperature calculated from our measurement data. The temperature was measured with a resolution of 0.3ºC.

In summary, we have demonstrated a new method to characterize Brillouin spectrum that can lead to simplified setups in various applications, especially in distributed sensing schemes. Moreover, it can open new ways to exploit the wavelength dependence of the stimulated Brillouin scattering effect for sensing applications.

References

[1] M. Sagues, A. Loayssa and J. Capmany, "Multitap complex-coefficient incoherent microwave photonic filters based on stimulated Brillouin scattering," *IEEE Photonics Technology Letters*, vol. 19, pp. 1194-1196, 2007.

[2] A. Zornoza, D. Olier, M. Sagues, A. Loayssa, "Distortion-free Brillouin distributed sensor using RF shaping of pump pulses, " in *Proc. IEEE sensors conference*, Christchurch, 2009, pp.433–436.

[3] A. Loayssa, D. Benito and M. J. Garde, "Optical carrier-suppression technique with a Brillouin-erbium fiber laser," *Opt. Lett.*, vol. 25, pp. 197-199, 2000.

[4] W. Zou, Z. He and K. Hotate, "Investigation of strain- and temperature-dependences of Brillouin frequency shifts in GeO2-doped optical fibers," *J. Lightwave Technol.*, vol. 26, pp. 1854-1861, 2008.