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Distributed fiber-optic frequency-domain Brillouin sensing

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Abstract

The experimental validation of a full frequency-domain fiber-optic Brillouin sensing technique for temperature/strain measurements is presented. An original formulation is employed which relates the frequency-domain measurements to the Brillouin gain profile along the sensing fiber, useful to both improve the signal-to-noise ratio and to cope with the non-local effects occurring when long measurement distances are involved. By this formulation, a reconstruction algorithm is derived which determines the temperature/strain profile that provides a best fit to the measured data. Preliminary experimental results confirm the validity of the proposed technique.

Keywords: Brillouin scattering; Temperature sensors; Strain sensors

1. Introduction

Stimulated Brillouin scattering (SBS) in optical fibers permits to measure temperature and/or strain on a truly distributed basis, over kilometric ranges with high resolution. The SBS effect is the result of the interaction between two counter-propagating lightwaves with frequency shift v and an acoustic wave of frequency v, the latter being generated by the lightwaves themselves through the process of electrostriction [1]. In this three-wave mixing process, power is transferred from the pump lightwave to the stokes lightwave (that is the lightwave having a lower frequency) and also to the acoustic wave. The coupling between the two optical waves occurs due to Bragg diffraction of the light from the refractive index perturbation produced by the acoustic field. The interaction process is described by the Brillouin gain coefficient $g(v)$, which depends on the frequency shift v and attains its maximum at the so-called Brillouin frequency shift v_B. As the Brillouin frequency shift changes linearly with temperature and strain, a distributed temperature–strain sensor can be realized using stimulated Brillouin scattering.

A method to resolve spatially the Brillouin frequency shift along the fiber consists of using a sinusoidally intensity modulated pump lightwave. This latter interacts with a counter-propagating CW probe lightwave, so that this latter is intensity-modulated at the same frequency. By measuring the induced complex AC component for a range of modulation frequencies, the base-band transfer function of the sensing fiber is achieved [2]. Such a frequency-domain approach permits a high signal-to-noise ratio to be achieved, due to synchronous signal detection. Frequency-domain data are usually inverse Fourier-transformed, so as to extract the Brillouin gain spectrum at each section along the fiber, and then to estimate the Brillouin frequency shift at any of these sections. Recently, a novel reconstruction technique, named harmonic technique, for distributed fiber-optic Brillouin sensing in the frequency-domain has been proposed [3]. In this approach, an original formulation is employed which directly relates the transfer function (TF) to the Brillouin gain profile along the fiber. Numerical tests have proved the capability of the proposed technique in accurately determining the Brillouin frequency shift profile along the sensor. In particular, the harmonic approach has been demonstrated to be superior to the direct spectroscopic approach, in its capability to compensate for non-local effects, affecting the quality of the

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reconstruction when high powers and/or long sensing lengths are involved [3,4]. In this paper, the experimental validation of the proposed approach is presented. Frequency-domain SBS measurements are carried out by means of a Brillouin optical frequency-domain analysis (BOFDA) configuration, featuring a single laser source for the generation of both the pump and the probe lightwaves.

The paper is organized as follows. In Section 2, we introduce the equations describing the Brillouin scattering and derive, in the frequency-domain, an integral equation, which directly relates the Brillouin gain to the Brillouin signal. In Section 3, we describe the reconstruction technique. Finally, in Section 4 the experimental set-up employed for the SBS measurements and the reconstruction of some temperature profiles, achieved by applying the proposed algorithm, are presented. Conclusions follow in Section 5.

2. Frequency-domain theory

Provided that the modulation frequency does not exceed the Brillouin gain spectrum bandwidth of several tens of MHz [2], the Brillouin interaction can be described by a set of two coupled equations for the pump and the Stokes intensities:

$$\left(\frac{1}{v_g}\frac{\partial}{\partial t}+\frac{\partial}{\partial z}+\alpha\right) I_{CW} = -g I_{CW} I_{mod} \tag{1}$$

$$\left(\frac{1}{v_g}\frac{\partial}{\partial t}-\frac{\partial}{\partial z}+\alpha\right) I_{mod} = g I_{CW} I_{mod} \tag{2}$$

where $I_{CW}(z, t)$ and $I_{mod}(z, t)$ are the intensities of the CW wave and the modulated wave, respectively, $g(z, v)$ the Brillouin gain, α the fiber loss coefficient, v_g the group velocity in the fiber and z is the axial displacement along the fiber. The boundary conditions are:

$$\begin{aligned} I_{CW}(0,t) &= I_{CW0\_0} \\ I_{mod}(L,t) &= I_{mod0\_L} + I_{mod1\_L}\cos(\omega t) \end{aligned} \tag{3}$$

where L is the length of the fiber. Hence, a CW wave with intensity I_{CW0_0} is injected at $z = 0$, whereas a modulated wave is injected at $z = L$.

Due to SBS interaction between the two beams, the CW wave intensity is modulated at the angular frequency ω as the lightwave propagates from displacement $z = 0$ to L. Hence, we can express the intensities of the two waves as:

$$\begin{aligned} I_{CW}(z,t) &= I_{CW0}(z) + Re\{I_{CW1}(z)\exp(j\omega t)\} \\ I_{mod}(z,t) &= I_{mod0}(z) + Re\{I_{mod1}(z)\exp(j\omega t)\} \end{aligned} \tag{4}$$

where $I_{CW0}(z)$ and $I_{mod0}(z)$ are the steady-state solutions of Eqs. (1) and (2).

Using Eq. (4), Eqs. (1) and (2) can be rewritten as:

$$\begin{aligned} &\frac{dI_{CW1}}{dz}\exp(j\omega t) \\ &= -\left(j\frac{\omega}{v}+\alpha\right) I_{CW1}\exp(j\omega t) - g(I_{CW1}I_{mod0}\exp(j\omega t) \\ &\quad + I_{CW0}I_{mod1}\exp(j\omega t) + I_{CW1}I_{mod1}\exp(j2\omega t)) \end{aligned} \tag{5}$$

$$\begin{aligned} &\frac{dI_{mod1}}{dz}\exp(j\omega t) \\ &= \left(j\frac{\omega}{v}+\alpha\right) I_{mod1}\exp(j\omega t) - g(I_{mod0}I_{CW1}\exp(j\omega t) \\ &\quad + I_{mod1}I_{CW0}\exp(j\omega t) + I_{mod1}I_{CW1}\exp(j2\omega t)) \end{aligned} \tag{6}$$

If we suppose that a small signal approximation model holds true, due to small modulation depth ($I_{mod0} \gg I_{mod1}$), we can neglect the second order term $I_{CW1}I_{mod1}\exp(j2\omega t)$ in Eqs. (5) and (6). Furthermore, if the measurements are performed by a synchronous detection using a vector analyzer [2], the second order terms do not contribute to the measured signal, as only the fundamental harmonic of the response is determined. So, for the above assumption, Eqs. (5) and (6) can be simplified as:

$$\frac{dI_{CW1}}{dz} = -\left(j\frac{\omega}{v}+\alpha\right) I_{CW1} - g(I_{CW1}I_{mod0} + I_{CW0}I_{mod1}) \tag{7}$$

$$\frac{dI_{mod1}}{dz} = \left(j\frac{\omega}{v}+\alpha\right) I_{mod1} - g(I_{mod0}I_{CW1} + I_{mod1}I_{CW0}) \tag{8}$$

To obtain a good signal-to-noise ratio, in practical measurement configurations it happens that $I_{CW0} \gg I_{mod0}$ [2]. If this assumption is valid, the third term on the right side of Eq. (8) ($gI_{mod0}I_{CW1}$) can be neglected. Owing to such simplification Eq. (8) can be directly solved, thus leading to a closed form expression for the modulated component of the stokes intensity, that is:

$$\begin{aligned} I_{mod1}(z,\omega) &= I_{mod1\_0}\exp\left[-\left(j\frac{\omega}{v}+\alpha\right)(L-z)\right] \\ &\quad\times \exp\left[\int_z^L g(z')I_{CW0}(z')dz'\right] \end{aligned} \tag{9}$$

Now, by substituting Eq. (9) into Eq. (7) and integrating the result along the fiber, we obtain

$$\begin{aligned} H(\omega) &\equiv \frac{I_{CW1}(L,\omega)}{I_{mod1\_L}} \\ &= -\exp\left[-2\left(j\frac{\omega}{v}+\alpha\right)L\right]\int_0^L g(z'')I_{CW0}(z'') \\ &\quad\times \exp\left[\int_{z''}^L g(z')[I_{CW0}(z') - I_{mod0}(z')dz']\right] \\ &\quad\times \exp\left[2\left(j\frac{\omega}{v}+\alpha\right)z''\right]dz'' \end{aligned} \tag{10}$$

This equation permits base-band transfer function $H(\omega)$ to be directly related the to the Brillouin gain profile $g(z)$ along the fiber. Note that the main integral in Eq. (10) can be interpreted as a Fourier-transform so it can be efficiently evaluated by the use of fast Fourier-transform techniques.