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Simulations and Measurements of Spontaneously Initiated Brillouin Scattering in Optical Fibers

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Abstract *Using a stochastic model, we simulate the spontaneously initiated Brillouin scattering in a single-mode optical fiber. In comparing our model with measurements, we find that the model successfully reproduces both the characteristics of the stochastic time traces and the resulting spectra.*

Introduction

Understanding Brillouin scattering in optical fibers is important for many applications such as fiber lasers, optical nonlinear signal processing and sensing. Within distributed optical fiber sensors, Brillouin scattering is used for monitoring temperature and strain along a fiber[1]. In Brillouin optical time domain reflectometers (BOTDR), the backward travelling Brillouin scattered electric field is spontaneously initiated by the thermal acoustic field when a forward travelling probe electric field is launched into the fiber. Stochastic models are needed to describe the time-dynamics of the spontaneously initiated Brillouin scattering. Such stochastic models on Brillouin scattering in optical waveguides have already been developed[2]–[5]. However, the models are rarely applied in the context of distributed fiber optic sensing. Introducing such a model for fiber-optic sensing allows for investigations on how the Brillouin field depends on e.g. pulse shapes, pulse lengths, input power and laser noise. In addition, nonlinear effects such as self phase modulation can easily be incorporated in the model, and the model can be expanded to include many acoustic and optical modes.

In this paper, we apply a stochastic propagation model[5] on a single-mode optical fiber with the goal of verifying the model to experimental data. We show that the model describes well the time dynamics and spectrum of the Brillouin scattering without fitting any physical parameters.

Simulations

The Brillouin scattering process is modelled using the following system of stochastic differential equations[2],[4]

$$\frac{\partial A_{pr}}{\partial z} + \frac{1}{v_g}\frac{\partial A_{pr}}{\partial t} + \frac{1}{2}\alpha A_{pr} = i\omega_{pr} Q A_b B, \tag{1a}$$

$$\frac{\partial A_b}{\partial z} - \frac{1}{v_g}\frac{\partial A_b}{\partial t} - \frac{1}{2}\alpha A_b = i\omega_b Q A_{pr} B^*, \tag{1b}$$

$$\frac{\partial B}{\partial z} + \frac{1}{v_{ac}}\frac{\partial B}{\partial t} + \frac{1}{2}\alpha_{ac} B = i\Omega Q A_b^* A_{pr} + \sqrt{\sigma} R(z,t), \tag{1c}$$

where $A_{pr}(z,t)$, $A_b(z,t)$ are the envelope electric field amplitudes (units $\sqrt{\mathrm{W}}$) of the forward travelling probe and backward travelling Brillouin scattered field, and $B(z,t)$ is the envelope acoustic field amplitude (unit $\sqrt{\mathrm{W}}$). $|A_{pr}|^2$, $|A_b^2|$ and $|B|^2$ are powers in the electric and acoustic fields. The envelope fields are related to the scalar electric fields E (unit V/m) and the longitudinal acoustic displacement field U (unit m) as[4]

$$E_{pr} = A_{pr}(z,t)F_{pr}(x,y)e^{i(k_{pr}z-\omega_{pr}t)} + c.c., \tag{2a}$$

$$E_b = A_b(z,t)F_b(x,y)e^{-i(k_b z+\omega_b t)} + c.c., \tag{2b}$$

$$U = B(z,t)F_{ac}(x,y)e^{i(k_{ac}z-\Omega t)} + c.c., \tag{2c}$$

where $F_{pr}(x,y)$, $F_b(x,y)$ and $F_{ac}(x,y)$ are the modal distributions of the electric and acoustic fields. $R(z,t)$ is a normally distributed stochastic variable with zero mean and unity variance, $R(z,t) \sim \mathcal{N}(0,1)$, which is uncorrelated in space and time $\langle R(z,t)R^*(z',t')\rangle = \delta(t-t')\delta(z-z')$. $\sigma = k_B T \alpha_{ac}$ is the strength of the thermal noise. v_g and v_{ac} are the optical and acoustic group velocities, and α, α_{ac} are the corresponding fiber losses. ω_{pr}, ω_b and $\Omega = \omega_{pr} - \omega_b$ are the angular frequencies of the fields, and Q is related to the Brillouin gain factor g_0 (unit 1/(W·km)) as[5]

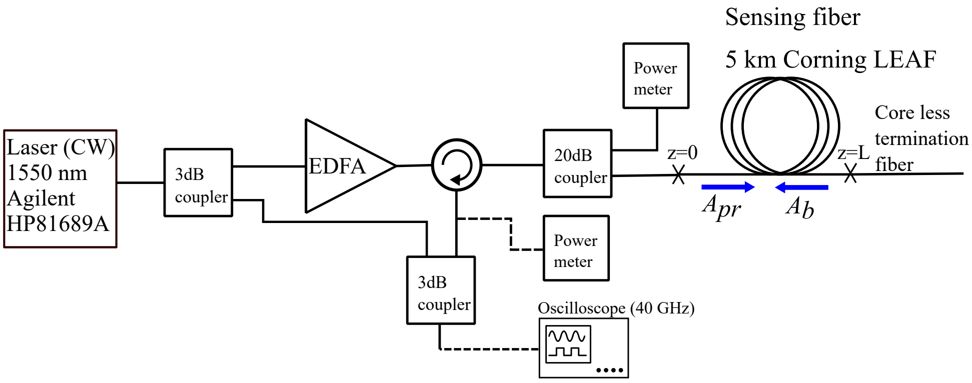


Fig. 1: The experimental setup. A_{pr} is the amplitude of the CW probe field which we launch into the fiber. A_b is the amplitude of the backward travelling Brillouin scattered electric field. The power meter after the 20 dB coupler is used to monitor the probe power launched into the fiber. The power meter before the 3 dB coupler is used to measure the reflected power from the fiber. The termination fiber is used to avoid reflections from the end facet of the sensing fiber.

$g_0 = 4\omega_b \Omega |Q|^2/\alpha_{ac}$. The gain factor g_0 and the acoustic loss factor α_{ac} are found using an in-house developed acoustic mode solver[7]. For simplicity, the current model takes into account only the interaction between the electric fields and a single acoustic mode. However, the fiber concerned in this work guides several acoustic modes, and thus only the acoustic mode giving the largest Brillouin gain factor is included in the model. In addition, the model assumes linearly and co-polarized electric fields along the fiber, although this is not realistic in real non-polarization maintaining fibers.

The equations Eq. (1) are solved numerically using the Euler-Mayurama scheme[5].

Experimental Setup

In order to validate the model, we have measured the Brillouin scattered field from a 5 km Corning LEAF optical fiber. The specific fiber was chosen since it is single-moded and since it was available at the time of measurements. The measurement setup is shown in Figure 1. A CW probe field is launched into the fiber, and the reflected Brillouin field is mixed with a local oscillator and sampled on a 40 GHz oscilloscope. The detected optical power in the heterodyne detection is $P_{opt}(t) \propto (E_{LO}+E_b)^2 = E_b^2 + E_{LO}^2 + 2E_{LO}E_b$ where E_{LO} is the local oscillator electric field. Letting $E_{LO}(t) = E_{LO}^0(t)e^{-i\omega_{pr}t} + c.c.$ and $E_b(t) = E_b^0(t)e^{-i\omega_b t} + c.c.$, where $E_{LO}^0(t)$ and $E_b^0(t)$ are the envelope fields, the beat term $E_{LO}E_b$ becomes

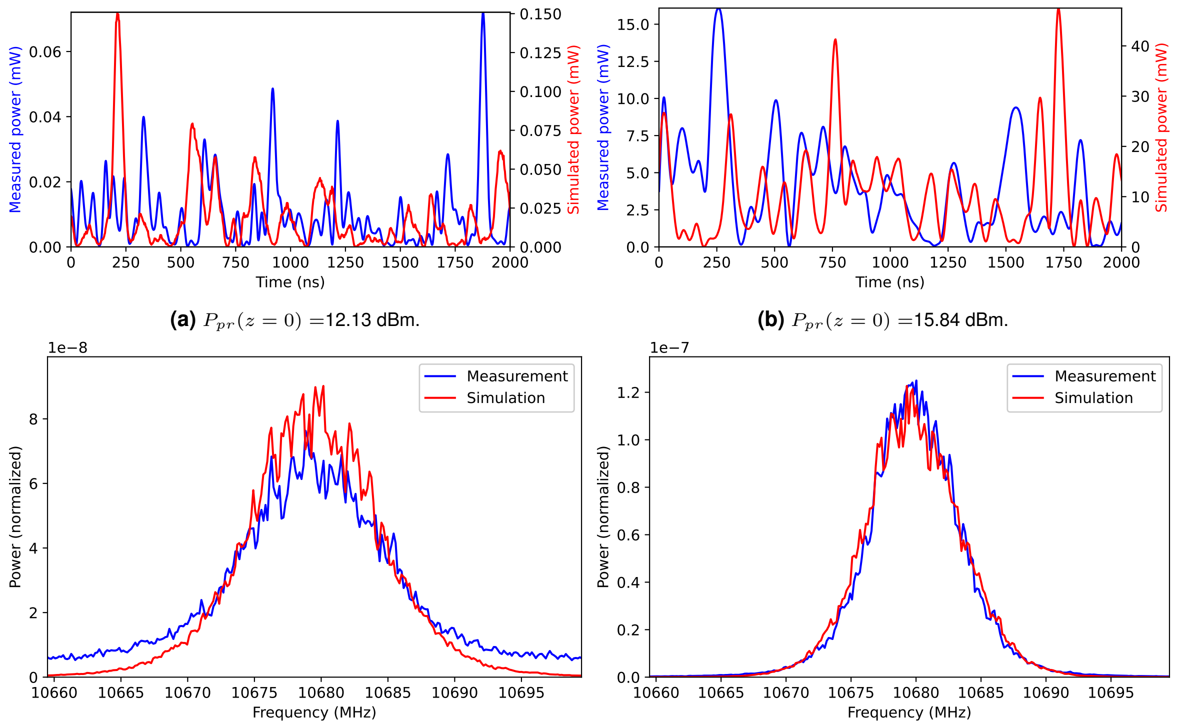
$$\begin{aligned} E_{LO}E_b =& E_{LO}^0 E_b^0 e^{-i(\omega_{pr}+\omega_b)t} \\ &+ E_{LO}^0 E_b^{0*} e^{-i\Omega t} + c.c., \end{aligned} \tag{3}$$

where $\Omega = \omega_{pr} - \omega_b$. From this expression, we extract the term $E_{LO}^0 E_b^{0*} e^{-i\Omega t}$ in the digital post processing through filtering. In order to extract the Brillouin envelope field $E_b^0(t)$, we assume that the local oscillator is an ideal CW field with linewidth much smaller than the width of the Brillouin spectrum. This means that E_{LO}^0 is approximately a constant. From this assumption, we attribute the time dependence of the beat term to $E_b^0(t)e^{-i\Omega t}$. The average power level of the Brillouin scattered field has been measured on a power meter before the mixing with the local oscillator. This allows us to scale the measured time trace in the digital post processing such that the average power of the time trace corresponds to the measured average power. Since we apply no filter on this power meter, the measured power has contributions both from Rayleigh and Brillouin scattering. We measured the Brillouin threshold to be 12.2 dBm, which we define as the probe power where the powers in the Brillouin and Rayleigh fields are equal.

Results and Discussion

We simulated and measured the time traces of the Brillouin scattered field for two different probe input powers, $P_{pr}(z=0) = 15.8$ dBm and $P_{pr}(z=0) = 12.1$ dBm. The results are shown in Figure 2. We use the following model parameters for the simulations: $g_0 = 13.6$ 1/(W·km), $v_g = 2.07 \cdot 10^8$ m/s, $\alpha = 0.19$ dB/km, $\lambda_{pr} \approx \lambda_b = 1550$ nm, $v_{ac} = 5708$ m/s, $\alpha_{ac} = 4.2 \cdot 10^4$ 1/m, $T = 295$ K. For the model boundary conditions, we use $A_{pr}(z=0, t>0) = \sqrt{P_{pr}}$ and $A_b(z=L, t) = 0$. We also let $A_{pr}(z, t=0) = A_b(z, t=0) = 0$ and run the simulation until steady-state has been achieved. All parameters used in the model are extracted from data sheets or from our numerical mode solver, meaning that no fitting parameters have been used.

We see good agreement between simulations



(a) $P_{pr}(z=0)$ =12.13 dBm. **(b)** $P_{pr}(z=0)$ =15.84 dBm.

(c) $P_{pr}(z=0)$ =12.13 dBm. **(d)** $P_{pr}(z=0)$ =15.84 dBm.

Fig. 2: (a) and (b) show the simulated and measured time traces of the power of the Brillouin field, $|A_b(z=0,t)|^2$. The power levels on the measured time traces have been adjusted such that the average power corresponds to the average power measured using the power meter in Figure 1. (c) and (d) show the corresponding spectra of $A_b(z=0,t)$. All spectra are obtained by applying Welch's method[6] on single time traces (which are longer than the time traces shown in (a) and (b)) and normalized such that the areas under the curves seen on the figures are unity.

and measurements, both when considering the time traces and the spectra. For the P_{pr} =12.13 dBm spectrum in Figure 2(c), the detector noise floor is visible and is the reason for the discrepancy at the tails of the spectrum. The width of the Brillouin spectrum is known to depend on the probe power[3], and the effect is also seen when comparing the spectra on Figure 2(c) and Figure 2(d).

From the time traces, we see that the power levels of the measurements and simulations deviate significantly. Our model assumes linear and co-polarized electric fields in the fiber but in reality the polarization state changes along the fiber which leads to a reduction of the total Brillouin gain.

Notice from Figure 2(c-d) that the fluctuations on the spectra are similar for simulations and measurements. The ability to model the noise on the spectra can be useful in distributed optical fiber sensing, where the peak frequency contains information of the temperature and strain of the fiber. Low signal to noise ratio on the spectrum is desirable for accurate determination of the peak frequency.

Conclusion

We have simulated and measured the spontaneously initiated Brillouin scattering in a Corning LEAF single-mode fiber. We find good agreement when comparing both the simulated/measured time traces and spectra. The model may be an important tool for simulation of distributed fiber optic sensors since it allows for further investigations on how e.g. laser noise and pulse shapes influence the Brillouin scattered field. In addition, it is possible to expand the model to include nonlinear effects like self phase modulation and to include several optical and acoustic modes for application in multi-mode fiber based sensing.

Acknowledgements

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