Long Variable Delay and Distributed Sensing Using Stationary and Localized Brillouin Dynamic Gratings

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Abstract: Stationary and localized Brillouin dynamic gratings are generated using phase modulation of both pump waves by a pseudo-random bit sequence. The gratings are applied to long variable delay of pulses and to cm-level distributed sensing.
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1. Introduction

Dynamic Brillouin gratings are introduced by two pump waves, which are co-polarized along one principal axis of a polarization maintaining (PM) fiber [1-7]. The stimulated Brillouin scattering (SBS) interaction between the pumps, which are spectrally detuned by the Brillouin shift Ω_B in the fiber, generates a traveling acoustic wave which is accompanied by refractive index variations. The acoustic wave can be switched on and off and even moved along the fiber, depending on the profiles of the pump waves. The dynamic grating is interrogated by a third, probe signal, which is polarized along the orthogonal principal axis of the PM fiber. Due to the PM fiber birefringence, the frequency of the reading signal must be detuned from those of the pumps, typically by a few tens of GHz [1]. The reading signal is back-reflected by the dynamic grating into a fourth wave, which is measured to monitor the entire process. Dynamic gratings have been drawing increasing interest, for their considerable potential performance enhancements of SBS applications. The use of a third and fourth optical frequencies in the readout process improves the signal to noise ratio of the measurements. The spectral offset between the pump and readout waves varies with the PM fiber birefringence, which in turn depends on both temperature and strain. Dynamic gratings therefore add another dimension to SBS-based distributed sensing [2,4]. In addition, dynamic gratings may provide ‘movable mirrors’, thereby introducing a new potential platform for all-optical variable group delay [5,6].

When both pumps are continuous waves (CW), a uniform dynamic grating is introduced along the entire PM fiber. Localized dynamic gratings have been generated using pump pulses [6,7]. However, an efficient generation of short gratings is restricted by the acoustic lifetime $\tau \sim 6$ ns. Brillouin optical correlation domain analysis (B-OCDA) was introduced to obtain stationary and localized dynamic gratings [3]. The technique relies on the synchronized frequency modulation of both pumps. However, the modulation introduces additional complexity, as the frequency of the readout probe signal must be synchronously modulated as well [3]. In addition, when simple sine-wave frequency modulation is used, tight trade-offs prevail between the B-OCDA range and resolution [8].

In this work, we propose and demonstrate a novel technique for the generation of stationary and localized dynamic gratings. The method relies on the phase modulation of the two pumps by a common pseudo-random bit sequence (PRBS), with a symbol duration that is much shorter than τ. The method confines the effective SBS interaction to discrete, cm-scale correlation peaks. The separation between neighboring correlation peaks is governed by the length of the PRBS, and can be made arbitrarily long. No modulation of the readout probe wave is necessary. Using this technique, we demonstrate the variable delay of 1-ns-long periodic pulses by as much as 770 ns, and the distributed sensing of temperature variations on a cm-level resolution, using a CW readout probe.

2. Principle of operation and simulations

Let us denote the complex envelopes of the two pump waves of an SBS dynamic grating as $A_{1,2}(t,z)$, respectively, where t stands for time and z represents position along a PM fiber of length L. Pump A_1 enters the fiber at $z = 0$ and propagates along the positive z direction, whereas pump A_2 propagates from $z = L$ in the negative z direction. The optical frequencies of the two pump waves are separated by $\Omega \sim \Omega_B$. The phases of both pump waves are modulated by a common PRBS with symbol duration $T << \tau$:

$$A_1(t, z=0) = A_2(t, z=L) = A(t) = A_0 \left\{ \sum_n \mathrm{rect}\left[(t - nT)/T \right] \exp(j\varphi_n) \right\} \qquad (1)$$

Here φ_n is a random phase which equals either 0 or π, $\mathrm{rect}(\xi)$ equals 1 for $|\xi| < 0.5$ and zero elsewhere, and A_0 denotes a constant magnitude. The modulation is synchronized so that the phases of $A_{1,2}(t,z)$, at their respective entry points into the fiber, are equal for all *t*. Both pumps are polarized along the $\hat{\mathbf{x}}$ principal axis of the fiber.

Consider next the magnitude of the acoustic density wave of frequency Ω that is generated by the two pumps. The temporal evolution of the density wave magnitude is governed by the following equation [9]:

$$\frac{\partial Q(t,z)}{\partial t} + j\frac{\Omega_B^2(z) - \Omega^2 - j\Omega\Gamma_B}{2\Omega} Q(t,z) = jg_1 A_1(t,z) A_2^*(t,z) \qquad (2)$$

In Eq. (2), $\Gamma_B = 1/\tau$ is the SBS linewidth, and the value of the parameter g_1 depends on the speed of sound in the fiber, its electrostrictive coefficient and density [9]. For brevity, we define the following notation: $\Gamma_A(\Omega,z) \equiv j\left[\left(\Omega_B^2 - \Omega^2 - j\Omega\Gamma_B\right)/2\Omega\right]$ [9]. On resonance ($\Omega = \Omega_B$), Γ_A reduces to its minimum value of $\frac{1}{2}\Gamma_B$.

Referring to our PRBS phase modulation scheme of Eq. (1), we can distinguish between the temporal evolutions of the acoustic dynamic grating in two regions. Within a short section surrounding $z = L/2$, the driving force for the acoustic grating generation (right hand side of Eq. (2)) is held fixed at $jg_1|A_0|^2$. Consequently, the acoustic grating in this region is allowed to build up to its steady state magnitude: $Q(t >> 1/\Gamma_A, z \approx L/2) = jg_1|A_0|^2/\Gamma_A(\Omega, z = L/2)$. The width of the correlation peak is on the order of $\Delta z = v_g T$, where v_g denotes the group velocity of light in the fiber. Outside the correlation peak, the sign of the driving force is randomly and rapidly alternating every *T*. The full buildup of the acoustic grating outside the correlation peak is therefore inhibited. In principle the symbol duration can be made arbitrarily short, however the grating reflectivity decreases with a shorter Δz. The separation between adjacent correlation peaks equals $\frac{1}{2}Mv_g T$, where *M* is the PRBS length. The correlation peaks, with the exception of the zeroth-order one, can be scanned across a fiber under test through changing *T*. Figure 1 (left) shows the simulated $Q(t,z)$ along a 1 m long fiber. The simulation predicts the build-up of a localized and stationary grating in a narrow region at the center of fiber, as suggested by the above considerations.

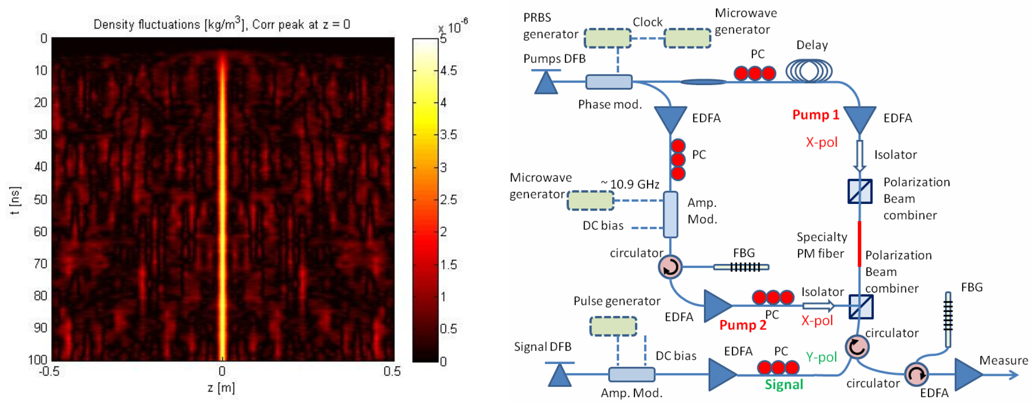

Fig. 1: Left - Simulated magnitude of the acoustic density wave $Q(t,z)$, T = 200 ps. Right - Experimental setup.

3. Experimental setup and results

Figure 1 (right) illustrates the experimental setup that was used in the generation and characterization of dynamic acoustic gratings, driven by phase modulation of both pump waves. The pump waves were launched into a specialty polarization maintaining (PM) fiber, and polarized along its $\hat{\mathbf{x}}$ principal axis. The generated acoustic gratings were interrogated by $\hat{\mathbf{y}}$ polarized readout signals. The frequency of the readout signals was tuned to match the peak reflectivity of the acoustic dynamic grating along the $\hat{\mathbf{y}}$ principal axis, as decreed by the fiber birefringence [1].

The localization of the dynamic gratings was demonstrated using periodic, isolated readout pulses that were 260 ps long (see Fig. 2, left). When CW pumps were used (curve a), a distributed reflection of the readout pulses was observed, suggesting that an extended, nearly uniform dynamic grating had been generated along the entire length of the 1 m-long fiber. Curves b and c show the temporal profiles of the reflected readout pulses with the

PRBS phase modulation of the pump waves switched on, using $T = 1$ ns and 167 ps, respectively. A reflection from a localized dynamic grating is evident. The variable delay of isolated readout pulses was demonstrated along a 100 m long fiber. In this experiment, a PRBS length $M = 2^{10} - 1$ was used in the pumps modulation, and a fiber delay imbalance was added to the path of pump 1 so that the 10th correlation peak scanned across the fiber through small-scale changes to T. Figure 2 (center) shows the relative delay of reflected pulses, by as much as 770 ns.

The localized and stationary dynamic gratings were employed in the distributed sensing of temperature variations. A 5 cm-long hot-spot was generated along a 1 m-long fiber. Figure 2 (right) shows the relative reflected power as a function of the grating position z and the frequency separation Ω between the two SBS pumps. The frequency of the readout probe wave was adjusted to its value of maximum reflectivity at the temperature of the hot-spot. As seen in the figure, interrogation of the dynamic grating is effective at the location of the hot spot only.

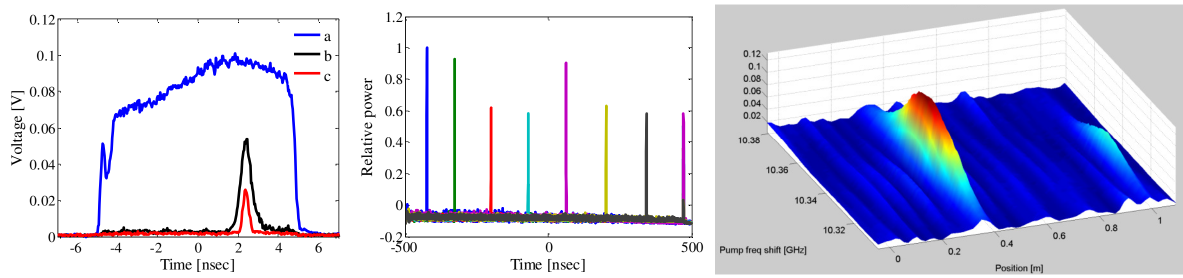

Fig. 2: Left – Reflected waveforms from dynamic gratings, interrogated with 260 ps long, isolated periodic readout pulses. a) CW pumps. b) The phases of both pumps were modulated by a PRBS, $T = 1$ ns. c) Same as b) with shorter bit duration, $T = 167$ ps.
Center – Variable delay of reflected isolated and periodic readout pulses. The rates $1/T$ of the pumps PRBS phase modulation were (left to right, in GHz): 1.120, 1.108, 1.093, 1.078, 1.063, 1.048, and 1.033.
Right – Measured relative power of a reflected readout signal from a 1 m long fiber, as a function of z and Ω. A 5 cm-long hot-spot was generated along the fiber. The frequency of the readout probe wave was set to its value of maximum reflectivity at the hot spot temperature.

3. Concluding remarks

A novel scheme for the generation of stationary and localized Brillouin dynamic gratings has been demonstrated. The gratings can provide movable mirrors for the variable delay of readout signals. The delay of readout pulses having ~ 4 GHz bandwidth and a delay-bandwidth product of 770 are reported. The bandwidth may be increased towards 10 GHz, and it is only limited by the reduced reflectivity of shorter gratings. The maximal delay is only restricted by the PM fiber length, and may reach the order of 10 μs. Distributed sensing with cm-level resolution using CW readout probe waves was demonstrated as well. The method is applicable to the variable delay of any periodic pulse pattern or analog signal, provided that the wave reflected from the dynamic grating may be averaged over multiple repetitions. The delay of one-shot optical communication data, however, is restricted by noise due to reflections from residual correlation sidelobes. Ongoing work is dedicated to quantifying the extent of noise using analysis, simulations and experiments, and to noise mitigation using advanced modulation codes. Lastly, the proposed scheme is equally applicable to the localization of pump-probe SBS interactions over standard fibers.

4. References

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