True Time Reversal through Dynamic Brillouin Gratings in Polarization Maintaining Fibers

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Abstract — **A novel technique to realize true time reversal of an optical signal, using dynamic Brillouin gratings in high-birefringence fibers, is proposed. A data sequence of optical pulses with 2-ns duration was efficiently time-reversed. A numerical simulation of the process confirmed the experimental results.**

1. INTRODUCTION

Time reversal of low frequency signals in electromagnetism and acoustics has been theoretically and experimentally demonstrated [1, 2, 3, 4], and present several potential applications in communications, medicine and material analysis. For example, in radio frequency transmission compensation of multipath interference can be realized through the time reversal mirrors [2].

Experimental demonstration of ultrafast optical waveform time reversal has been also achieved, using various physical phenomena such as spectrally decomposed-wave mixing [5, 6], photon echo [7], spectral hole-burning holography [8] and time lenses [10].

In this contribution, we propose and experimentally demonstrate a novel technique to perform true time reversal (TTR) of optical signals in an all-fiber configuration, by exploiting dynamic Brillouin gratings (DBG) in polarization maintaining (PM) optical fibers [9]. The proposed setup is simpler with respect to the all-fiber time-lens proposed in [10], and so very attractive for applications in optical communications and microwave-photonics [11]. The experimental results are corroborated by numerical simulations of the process. In sec. 2, we introduce the basic principle of the TTR obtained through DBG. In sec. 3 and sec. 4, we present and explain the setup for the experiments and the simulations, respectively. Finally, in sec. 5, we make the comparison between the experimental and the simulations results.

2. PHYSICAL PRINCIPLE OF TIME REVERSAL

Light storage and retrieval in optical fibers has been successfully demonstrated [12, 13] by exploiting stimulated Brillouin scattering (SBS) of two counter-propagating optical pulses: a data waveform, at frequency ν_d^{in} and a write pulse at frequency ν_w . If the $\nu_d^{in} - \nu_w = \nu_B$ (about 10 GHz in silica fibers) an acoustic wave is generated through the electrostriction effect. The acoustic wave retains the characteristics of the data waveform and actually longitudinally modulates the fiber refractive index, thus creating a spatially localized grating. The DBG decays on a time scale of several ns and moves at the sound speed; so, over the short time of its life, it can be considered static. A new light beam (read pulse) injected from the same side of the write pulse and with the same frequency of the write pulse, can be scattered onto the DBG, thus enabling the original optical waveform to be retrieved [12, 13]. In PM fibers, the storage/retrieval processes can be decoupled by using separate orthogonal states of polarization aligned to the birefringence axis [9, 14] for the read and write pulses. In fact, the acoustic wave equally scatters all light polarizations owing to its longitudinal nature.

However, if the read pulse is injected from the other side with respect of the write pulse the scattered waveform is a time reversed version of the stored data. This principle is illustrated in Fig. 1. The linearly polarized input data sequence, $A_d^{in}(t)$, and the counter-propagating (write) pulse, $A_w(t)$, are launched along the slow axis of a PM fiber. The signals interact through SBS and generate the acoustic wave, Q. The reading pulse, A_r, linearly polarized along the fast axis is launched just after the data sequence, thus interacting with the stored acoustic wave and generating a counter-propagating output waveform, $A_d^{out}(t)$, which is polarized along the fast axis and have a frequency

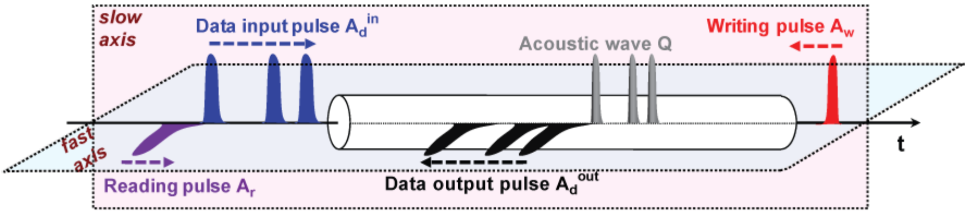

Figure 1: *Process for the realization of TTR in PM fibers via DBG.*

$\nu_d^{out} = \nu_r - \nu_B$. The part of the input sequence which was stored last is the first to be retrieved and so TTR is realized. Besides frequency matching, phase matching conditions between the optical waves and the acoustic waves must also be satisfied for the process to occur and one gets:

$$\nu_r = (1 + \Delta n/n_s)\nu_d^{in} \qquad (1)$$

where $\Delta n = n_s - n_f$ is the refractive index difference between orthogonally polarized waves, due to the fiber birefringence [9, 14].

3. EXPERIMENTS

To realize the experimental setup implementing the scheme of Fig. 1, a commercial distributed feedback (DFB) laser diode operating at a wavelength of 1535 nm is used as a light source and its output is split using a directional coupler.

On one branch (write) the radiation is fast-optically gated through an electro-optic Mach-Zehnder modulator (EOM), generating a pulse train with FWHM duration of 2 ns at a 1 MHz repetition rate. The write pulse is then generated by boosting the amplitude, using a high power Erbium doped fiber amplifier, (EDFA), up to a peak power of 160 W. The read pulse is generated in a similar way using a different DFB laser.

On the other branch, the data input pulse is obtained first by modulating the laser signal, through another EOM, at the Brillouin frequency shift. An adequate DC bias applied to the modulator enables a complete suppression of the carrier, so that only two sidebands remain at EOM output. The higher-frequency sideband is then removed with a filter (through a fiber Bragg grating); another EOM is used to generate a data waveform pulse with identical duration and repetition rate of the write pulse. The data sequence was obtained by combining three, differently delayed replicas of the data pulse finally obtaining a 101001 digital data sequence. The peak power is amplified using an EDFA to achieve the peak value of 500 mW. The input data pulse time trace is shown in Fig. 2. The data and write pulses are linearly polarized to match PM fiber axes using polarization controllers.

Accurate synchronization of data, write and read pulses is realized to assure that the DBG is generated and read well before it disappears (data - read time delay of about 1.5 ns). The carrier frequency of the read pulse is also precisely tuned in order to satisfy the SBS phase matching conditions 1), which yields $\nu_r - \nu_w \simeq 42GHz$.

4. MODEL

The process of DBG formation and TTR retrieval is governed by the following equations:

$$\begin{aligned}
\frac{\partial A_d^{in}}{\partial z} + \beta_{1s}\frac{\partial A_d^{in}}{\partial t} &= -\eta_1 g_B Q A_w + j\eta_2\gamma(|A_d^{in}|^2)A_d^{in}, && (2)\\
-\frac{\partial A_w}{\partial z}\beta_{1s}\frac{\partial A_w}{\partial t} &= \eta_1 g_B Q^* A_d^{in} + j\eta_2\gamma(|A_w|^2)A_w, && (3)\\
\frac{\partial A_r \partial z}{+}\beta_{1f}\frac{\partial A_r}{\partial t} &= -\eta_1 g_B Q A_d^{out} + j\eta_2\gamma(|A_r|^2)A_r, && (4)\\
-\frac{\partial A_d^{out}}{\partial z} + \beta_{1f}\frac{\partial A_d^{out}}{\partial t} &= \eta_1 g_B Q^* A_r + j\eta_2\gamma(|A_d^{out}|^2)A_d^{out}, && (5)\\
2\tau_B\frac{\partial Q}{\partial t} + Q &= A_d A_w^* + (A_d^{out})^* A_r. && (6)
\end{aligned}$$

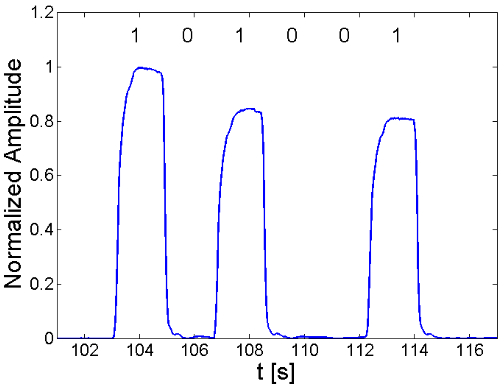

Figure 2: *Input data sequence, composed by 6 bits of duration 2 ns.*

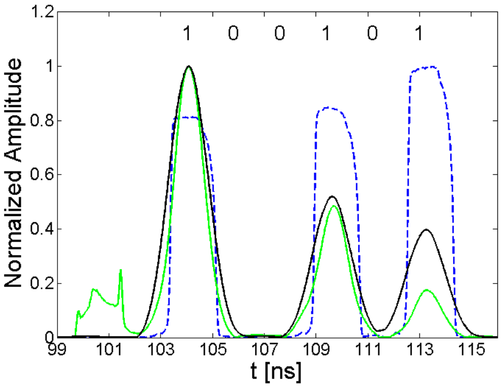

Figure 3: *Comparison of experimentally (green curve) and numerically (black curve) reversed sequence, with ideally reversed input sequence (blue curve). Write/read pulses of 2ns duration.*

where all waves $A_d^{in}, A_d^{out}, A_w, A_r, Q$ are functions of time t and space z. The main difference with Eqs. of ref. [14] is that the self phase modulation is taken into account because of the high peak power (>100 W) of the write/read pulses. The simulations are performed by numerically integrating Eqs. 2-6, through a split-step method. The parameters are set as the measured or estimated fiber parameters: fiber length $L = 20\ m$, data central wavelength $\lambda_d = 1535\ nm$, fiber birefringence $\Delta n = 5 \cdot 10^{-4}$, SBS shift $\nu_B = 10.93\ GHz$, SBS gain $g_B = 5 \cdot 10^{-11}\ m/W$, acoustic wave lifetime $\tau_B = 4\ ns$, nonlinearity coefficient $\gamma = 2.6 \cdot 10^{-3}\ m^{-1}W^{-1}$. $\eta_1 = 2 \cdot 10^{-3}\ \Omega^{-1}$ and $\eta_2 = 8 \cdot 10^{-14}\ \Omega^{-1} m^2$ are normalization factors.

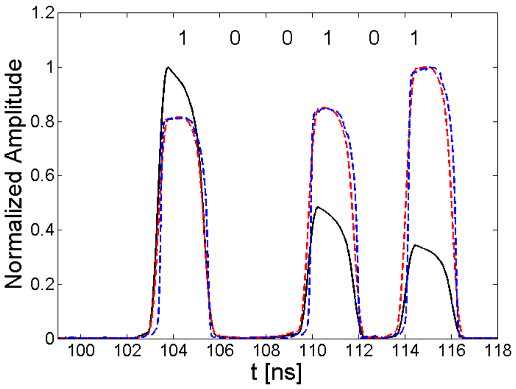

Figure 4: *Comparison of simulation results without (black curve) and with (red curve) the exponential post-correction (write/read pulses of 0.25ns duration) with ideally reversed input sequence (blue curve).*

5. RESULT ANALYSIS

In Fig. 3, TTR is experimentally demonstrated (green curve); the agreement with the numerical results (black curve) obtained with the input sequence of Fig. 2 is good. The weak leading pulse for $99.5 < t < 101.5\ ns$ is not observed numerically and is imputed to an imperfect coupling into the PM or a residual write pulse). Let us also notice that the output pulses are broader and weaker of those of an ideally reversed sequence (blue curve). The difference in the peak height is mainly due to the fact that the acoustic wave decays exponentially ($exp[-t/(2\tau_B)]$) while stored. So, the first bit to be stored, i.e. the last to be retrieved, is affected by a larger decay.

The pulse broadening, which is captured by the model is due to a spectral filtering effect; in fact during the write and read phase a convolution of pulses occurs, as can be demonstrated by direct integration of eq. 6. The explanations given for the observed experimental distortions are confirmed in Fig. 4, where we show the results of the same numerical integrations of Eqs. 2-6, with the input sequence of Fig. 2, by using shorter write/read pulses (0.25 ns) (black curve) and with a numerical post-compensation of the exponential decay (red curve).

6. CONCLUSIONS

A novel method to achieve true time reversal of optical signals has been proposed by exploiting dynamic Brillouin gratings in polarization maintaining fibers has been theoretical and experimentally demonstrated. A data sequence of 6, 2-ns optical bits has been experimentally time reversed. The numerical analysis is in good agreement with experiments and demonstrates that high-fidelity reversal can be achieved. Possible applications in electromagnetics [3] and MWP [11] can be envisaged.

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References

[1] R. Sorrentino, L. Roselli, P. Mezzanotte, "Time reversal in finite difference time domain method", IEEE MGW Lett. **30** (1993) 402.

[2] M. Fink, "Time-reversed acoustics," Physics Today **50** (1997) 34.

[3] G. Lerosey, et al., "Time Reversal of Electromagnetic waves," Phys. Rev. Lett. **92** (2005) 193904.

[4] H. T. Nguyen, J. B. Andersen and G. F. Pedersen, "The Potential Use of Time Reversal Techniques in Multiple Element Antenna Systems," IEEE Commun. Lett. **9** (2005) 40.

[5] D. A. B. Miller, "Time reversal of optical pulses by four-wave mixing," Opt. Lett. **5** (1980) 300.

[6] D. Marom, et al., "Time reversal of ultra- fast waveforms by wave mixing of spectrally decomposed waves," Opt. Lett. **25** (2000) 132.

[7] N. W. Carlson et al., "Storage and time reversal of light pulses using photon echoes," Opt. Lett. **8** (1983) 483.

[8] A. Rebane , J. Aaviksoo and J. Kuhl, "Storage and time reversal of femtosecond light signals via persistent spectral hole burning holography," Appl. Phys. Lett. **54** (1989) 93.

[9] K. Y. Song et al., "All-optical dynamic grating generation based on Brillouin scattering in polarization maintain- ing fiber," Opt. Lett., **33** (2008) 926.

[10] F. Coppinger, A.S. Bhushan and B. Jalali, "Time reversal of broadband microwave signals," Electronics Lett. **35** (1999) 1230.

[11] J. Capmany, D. Novak, "Microwave photonics combines two worlds," Nature Photonics **1** (2007) 319.

[12] Z. Zhu, D. J. Gauthier and R. W. Boyd, "Stored light in an optical fiber via stimulated Brillouin scattering," Science **318** (2008) 1748.

[13] Y.Cao et al., "An efficient method of all-optical buffering with ultra-small core photonic crystal fibers," Opt. Expr. **16** (2008) 14142.

[14] V.P. Kalosha et al.,Bao, "Frequency-shifted light storage via stimu- lated Brillouin scattering in optical fibers," Opt. Lett. **33** (2008) 2048.