Ultra wide range tunable delay line using dynamic grating reflectors in optical fibers

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Abstract: We experimentally demonstrate a novel technique to realize a tunable delay line based on dynamic Brillouin gratings in a high birefringence fiber. A 8ns pulse signal is continuously delayed up to 184ns with minor distortion. ©2010 Optical Society of America

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1. Introduction

The realization of all-optically controlled delay lines has been one of the great scientific challenges in the photonic community, since they have proved to be a necessary stage towards all-optical signal processing in optical communication systems. Over the last decade, many experiments on signal delaying have been successfully demonstrated using a variety of physical mechanisms [1,2]. However, most delaying systems rely on two major techniques: slow light and dispersive delay line. The possibility to generate slow light in optical fibers using stimulated scatterings and optical parametric processes led to a significant step towards real applications due to their inherent advantages such as room temperature operation at any wavelength, large signal bandwidth and compatibility with fiber-optic communication systems [3]. Yet, the maximum delay in all slow light systems that a signal pulse can experience is essentially restricted to a few pulse-widths due to the large signal distortion, which in turn limits the delay-bandwidth product. An alternative method was soon proposed to improve to a large increment the pulse fractional delay, based on the combination of wavelength conversion and group velocity dispersion in an optical medium [4-6]. However, this type of delay line also needs novel solutions, especially when considering the efficiency of wavelength conversion and the inevitable signal distortion accompanying time delays, resulting from group velocity dispersion.

In this paper, we propose a novel technique to achieve reconfigurable signal delaying over an ultra wide range, breaking the delay-bandwidth product. It makes use of dynamic Brillouin gratings in polarization maintaining fibers (PMF), where the gratings acting as reflectors can be created at any preset position along the fiber. Therefore, a signal pulse can undergo the Bragg reflection at different points in the fiber and the time delaying results simply from the time-of-flight difference for the back-reflected signals. Using this new concept, it is clearly observed that a 8 ns signal pulse can be continuously delayed up to 184 ns in a 20m fiber with minor distortion, corresponding to a 23-bits fractional delay.

2. Principle

The tunable delay line is based on a principle using two distinct processes: a) Generation of a localized Brillouin dynamic grating (BDG) in the PMF using SBS in one polarization axis and b) reflection of the signal over the generated BDG in the orthogonal polarization axis at a distinct frequency. As it was already shown in previous reports [7, 8], it is possible to generate a Brillouin dynamic grating in PMF along one fixed polarization and observe the scattering from this grating in the orthogonal polarization at a shifted frequency. Figure 1 represents the principle of our experiment and visually demonstrates the polarizations of interacting beams as well as their relative frequency positions. Pulses of Pump 1 (ν_1) and Pump 2 (ν_2) are counterpropagating in one polarization direction of a PMF with a frequency difference equal to the Brillouin shift (ν_B). At their crossing position in the fiber an acoustic wave is generated as a result of the standard SBS process. If a signal pulse with orthogonal polarization and at the proper optical frequency ($\nu_S=\nu_1+\Delta\nu$) enters the crossing zone within the lifetime of the Brillouin acoustic grating it will be backscattered with a frequency ($\nu_R=\nu_S-\nu_B$) down-shifted from ν_S by the Brillouin frequency shift ν_B. The frequency difference $\Delta\nu$ is given by the local birefringence of the fiber ($\Delta n=n_x-n_y$) and can be calculated using the expression [7]:

$$\Delta\nu=\frac{\Delta n}{n}\nu,$$

where ν is the optical frequency of Pump 1 and n is the average refractive index of the fiber. Simply by applying a delay on Pump 2 pulse any crossing point of the two pumps can be addressed, hence any position of the Brillouin dynamic grating. As a consequence reflection of the signal pulse will also experience a relative delay which is twice larger due to the round trip propagation of the signal. In this experiment we change the position of the generated BDG and observe the delay for the signal pulse.

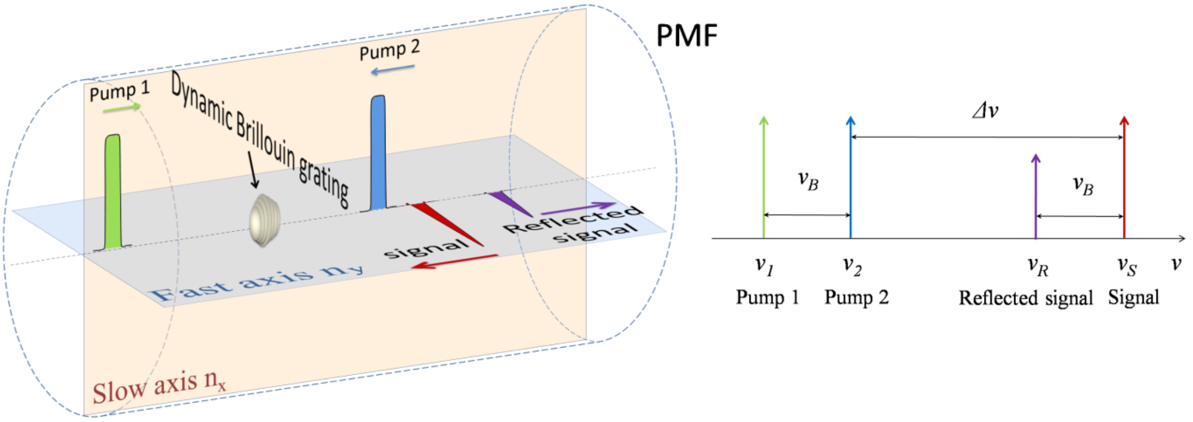

Fig. 1. Principle to generate localized Brillouin dynamic grating in PMF

3. Experimental setup and Results

Figure 2 depicts the schematic diagram of the experimental setup to produce signal delays. As Brillouin gain medium, a 20 m Panda type PMF was used, showing a Brillouin frequency ν_B of 10.93 GHz and a Brillouin gain bandwidth of 30 MHz; the birefringence Δn of the PMF was estimated to be $\Delta n \approx 5.151\times10^{-4}$ according to the Brillouin frequency difference between the two orthogonal polarization axes. A commercial distributed-feedback (DFB) laser diode operating at 1535 nm was used as a light source. Its output was split in order to produce two pump pulses. One branch was shaped as a pulse using an electro-optical Mach-Zehnder modulator (EOM), generating a 3 ns pulse train at 1 MHz repetition rate. Then the pulse at the output of the modulator was strongly boosted using a high power 30 dBm erbium doped fiber amplifier (EDFA) so as to play the role of Brillouin Pump 1, showing a peak power of 200 W. The pulsed Pump 1 was sent into a linear polarizer along the slow axis and the transmission was maximized using a polarization controller. Then it was delivered into one end of the PM fiber. The other branch was also fast-optically gated through an external modulator to generate the Brillouin Pump 2. Consequently, a 3 ns pulse train was produced at 1 MHz repetition rate. The output pulse was modulated through another external EOM at the Brillouin frequency of the PMF so as to generate two first-order sidebands, resulting in the generation of frequency-shifted optical pulse trains. Only the higher frequency sideband at the anti-Stokes frequency was precisely filtered and amplified by an EDFA to be used as Brillouin Pump 2, showing a 6 W peak power. In turn the polarization state of Pump 2 was aligned like Pump 1 along the slow axis and launched into the other end of the PM fiber. The relative time delay between Pump 1 and Pump 2 can be accurately set to place the dynamic Brillouin grating at any position along the PM fiber.

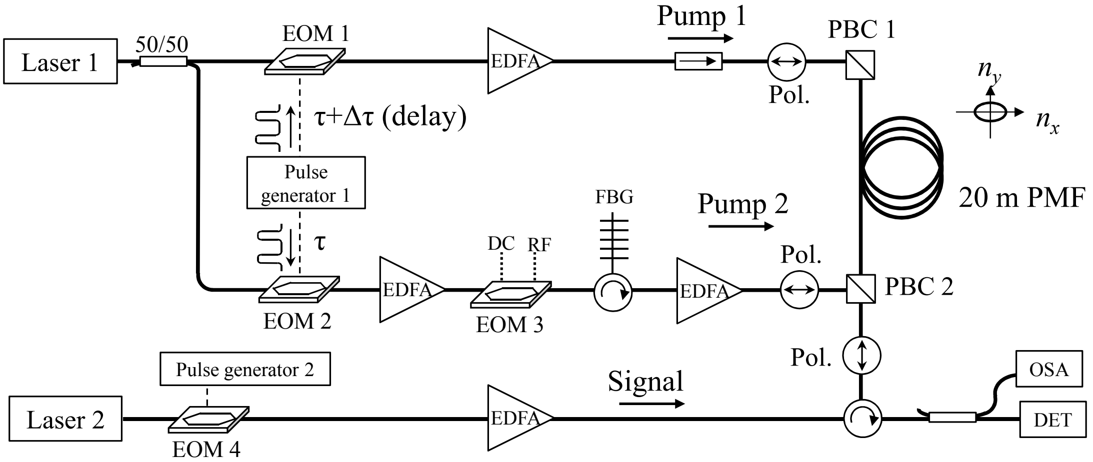

Fig. 2. Experimental setup to realize BDG based delay line. EOM: electro-optic modulator; EDFA: Erbium doped fiber amplifier; FBG: fiber Bragg grating; Pol.: polarizer;

A distinct DFB laser was exploited to generate a signal pulse. The laser output was modulated through an external modulator at 1 MHz, generating a pulse train with FWHM duration of 8 ns. Then the pulsed signal was strongly amplified by a high power EDFA with 30 dBm saturation power, leading to a 100 W peak power. The polarization state of the signal pulse was orthogonally aligned with respect to the two Brillouin pumps. The signal pulse was combined with Pump 2 using a polarization beam combiner and launched into the PM fiber.

The time interval between the signal and Pump 2 was set at 2 ns so as to maximize the efficiency of Bragg reflection of the signal pulse while keeping a time separation. Moreover, the center frequency of the signal was precisely controlled by the current and temperature applied to the laser diode, so that the signal can be spectrally placed in the middle of the grating resonance. According to the birefringence of the fiber, the signal frequency was placed +43 GHz above the Pump 2 frequency.

The time waveforms of the reflected signal were monitored and recorded on a fast oscilloscope, as shown in Figure 3(a). Time delays of the back-reflected signal are clearly proportional to the grating position in fiber, showing a slope efficiency of 10.18 ns/m. The largest time delay achieved in this experiment was 184 ns, close to the 200 ns anticipated from the fiber length, equivalent to a fractional delay of 23 and showing a minor signal distortion. However, it must be mentioned that the amplitude and shape of the reflected pulse can be function of the dynamic grating location, since the inhomogeneous birefringence along the fiber can lead to a shift of the center frequency of the grating resonance; thereby the signal pulse would not be faithfully replicated and the choice of a fiber with a good birefringence uniformity appears crucial for this technique.

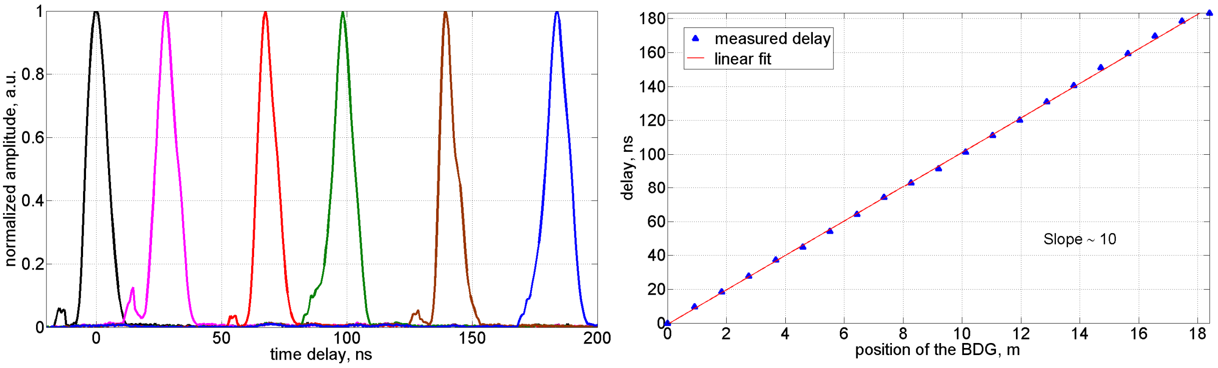

Fig. 3. (a) Selected signal waveforms for different true delays. (b) Measured time delays of the back-reflected signal pulse as a function of the delay set for pump 1 pulse and the red line represents the linear fitting.

4. Conclusions

We have described a new method for achieving large signal delays with low distortion in optical fibers, in which localized dynamic Brillouin grating is exploited to reflect the signal pulse. 8 ns signal pulses were continuously delayed by 100 ps steps up to 184 ns. It must be pointed out that the achievable maximum delay can be simply expanded by using a longer fibre. However, due to intrinsic fiber properties such as nonlinearities, polarization crosstalk and birefringence walk-off, the PM fiber cannot realistically extend over more than 1 km, showing nevertheless potentially continuous delay up to 10 µs. The technique for the moment works only for isolated pulses of limited badnwidth, but solutions are foreseen to make it suitable for a continuous data stream at high bit rate. This will be implemented and tested in the near future.

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