Brillouin-Based Random Fiber Optic Delay Line

Weiwen Zou, Zuyuan He, and Kazuo Hotate
Department of Electronic Engineering, The University of Tokyo, Tokyo 113-8656, Japan
Tel: +81 3 5841 6779, Fax: +81 3 5841 6025, E-mail: zou@sagnac.t.u-tokyo.ac.jp

Abstract: A continuous-wave light as Brillouin probe is linearly frequency-modulated to determine the location of the delayed pulse signal via stimulated Brillouin scattering. The random ~4-μs continuous tunability is experimentally demonstrated. The pulse distortion is also studied.

OCIS codes: (290.5900) Scattering, stimulated Brillouin; (060.2310) Fiber optics; (320.4240) Nanosecond phenomena.

1. Introduction

Fiber optic delay line is a key component for all-optical processing in telecommunication networks and for optical buffering and storage. Fiber Bragg gratings are capable of generating delay lines for optical pulse signals as cascaded in-line mirrors [1]. The grating's nature of selecting the particular pulse signal at the Bragg wavelength or frequency limits it as an invariable and discrete delay line. A new concept was recently demonstrated to obtain a tunable delay line by using Brillouin slow light [2-3]. In Brillouin slow light, the pulse signal as Brillouin probe is launched into the optical fiber to suffer Brillouin gain and thus slow-downed group velocity from an additional strong Brillouin pump via the acoustic grating intensified by the stimulated Brillouin scattering (SBS) effect. The experienced delay depending on the SBS gain is limited within several few pulse widths because of the depletion of pump power and the limited effective length of the silica-based fiber. The SBS acoustic grating can be localized at a particular position along a fiber by using a correlation-based technique [4]. Both optical lights serving as pump and probe lights, respectively, are frequency-modulated (FM) in a sinusoidal way and intensify the acoustic phonons in a position-dependent manner. This method was used as a dynamic grating to locally reflect a third optical light [5]. However, the real application in delay line is whittled down. One reason is that the SBS is not completely localized at only the correlation peak but happens at other locations [4]. Second, it is because the optical signal to be reflected or delayed should be synchronously FM in the same sinusoidal way as done the pump and probe lights [5].

In this work, we propose a novel method to generate fiber optic delay line based on SBS in an optical fiber, which is in principle totally different from the concept of Brillouin slow light [2-3] and the correlation-based technique [5]. In the novel method, the optical pulse signal to be delayed is reflected by the SBS acoustic grating at a particular location in the fiber. The location is determined by a counter-propagating continuous-wave (CW) light that is linearly modulated in frequency. The novel fiber optic delay line can be randomly programmable and has a linearly continuous tunability. The linearly tunable range of more than 4 μs for ~80-ns pulse signals is experimentally demonstrated. The pulse distortion is also studied and discussed.

2. Principles

Figure 1 depicts our proposal to generate a novel fiber optic delay line based on SBS. When a pulse signal enters into an optical fiber in +*z* direction [see Fig. 1(a)], weak pulse signals will be backscattered in –*z* direction along the entire fiber including Stokes or anti-Stokes of spontaneous Brillouin scattering (SpBS) and Rayleigh scattering [see Fig. 1(b)]. If a CW light is incident into the fiber's opposite end in –*z* direction with an optical frequency (f_{cw}) downshifted by ν_B (Brillouin frequency shift) from that of the pulse signal (f_s), the weak Stokes signal will be exponentially amplified due to SBS effect. The SBS amplification is an integral along the entire fiber.

If the optical frequency of the CW light is linearly modulated in terms of time, the optical pulse encounters the counter-propagating CW light with different optical frequency $f(z)$ at z [see Fig. 1(a)], which is expressed by

$$f(z) = f_{cw} + \Delta f * (z - L)/L , \qquad (1)$$

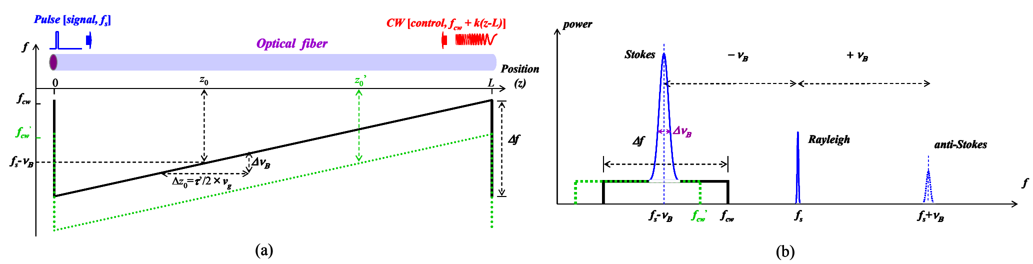


Fig. 1. Schematic principles of Brillouin-based random fiber optic delay lin. (a) Control scheme; (b) Optical spectra.

978-1-55752-865-0/09/$25.00 ©2009 IEEE

where Δf is the linear modulation depth and $L = T^*\mathrm{v}_g$ is the propagation distance that is decided by the linear modulation period (T) and the group velocity (v_g). As shown in Fig. 1(a), there is only one location (z_0) along the L-length fiber where $f(z_0) = f_s - \nu_B$ and the strong SBS occurs. The z_0 is the delay-line location:

$$z_0 = [(f_s - \nu_B) - f_{cw}] * L / \Delta f + L\,, \tag{2}$$

which determines the delay time $t_0 = 2^*z_0/\mathrm{v}_g$. When the modulation parameters (Δf and T or L) are fixed, the delay time is linearly increased by decreasing the CW light's f_{cw}. The linearly tunable rate is given by:

$$k = \delta t_0 / \delta f_{cw} = -2T / \Delta f\,. \tag{3}$$

Since the SBS has an intrinsic linewidth ($\Delta\nu_B$ = ~40 MHz) due to the damping of the acoustic phonons, there is a spatial zone (Δz_0) [see Fig. 1(a)], within which the pulse signal can be reflected in a Lorentz profile,

$$\Delta z_0 = \Delta \nu_B * (L / \Delta f)\,. \tag{4}$$

Correspondingly, the spatial zone determines the width of the delayed pulse (τ') as

$$\tau' = 2\Delta z_0 / \mathrm{v}_g = \Delta \nu_B * (2T / \Delta f)\,. \tag{5}$$

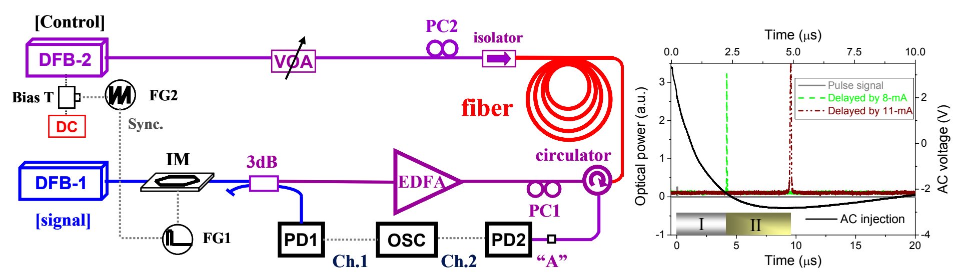
It is notable that Eq. (5) is proper unless the τ' is greater than the value (τ'') decided by the inverse law:

$$\tau'' = 1 / \Delta \nu_B\,. \tag{6}$$

3. Experimental details

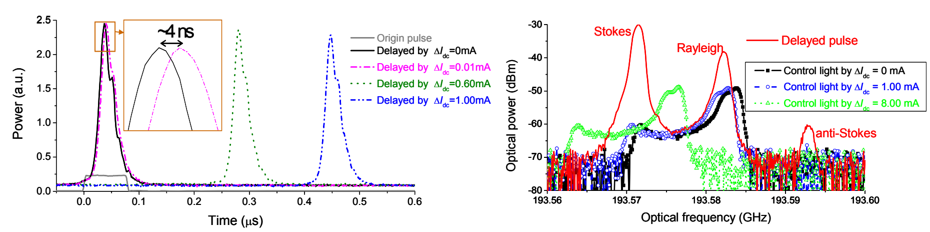
The experimental setup is depicted in Fig. 2 (a). 5-km single-mode optical fiber is used as a delay-line medium corresponding to one-way period of ~25-μs for optical light. A 1548.651-nm distributed-feedback laser diode (DFB-1, ~2-MHz linewidth) works as a source of the optical pulse signal to be delayed. A function generator (FG1) and an intensity modulator (IM) are introduced to generate a rectangular optical pulse signal (80-ns width, 50-μs repetition period). One part of the optical pulse is detected by a photo-diode (PD1) and recorded by an oscilloscope (OSC) as a reference and electrical trigger. The other part is amplified by an erbium-doped fiber amplifier (EDFA) as ~10 dBm and launched into the delay-line medium through a circulator. The CW light to control the fiber optic delay line is originated from a second DFB-2 (~2-MHz linewidth, also), whose central frequency f_{cw} can be tuned by changing its dc injection current (ΔI_{dc}) with a finest 0.01-mA step. A FG2 generates a 50-μs-period ramp-sweep electric waveform with 4.749-μs fall region and 45.251-μs rising region as the ac injection current to linearly modulate the optical frequency of the CW control light. The modulated CW light is attenuated by a variable optical attenuator (VOA) till ~ -30 dBm and incident into the other side of the delay-line medium through an isolator. The delayed pulse signals are detected by PD2 or measured by an optical spectrum analyzer (OSA) at the "A" adaptor.

Typical examples of the delayed pulses are illustrated in Fig. 2(b) where the delayed pulses are scaled by a fact-



(a) (b)

Fig. 2. Experimental setup (a) and an example of delayed pulses with 4.137-μs or 9.498-μs delay time (b). In (b), the electrical waveform of FG2 to the DFB-2 is scaled in right and top axes; the pulses are scaled in left and bottom axes.



(a) (b)

Fig. 3. (a) Magnified traces of delayed pulses with 0-ns, ~4-ns, ~244ns or ~410-ns delay time. (b) Optical spectra of reflected pulse and CW control lights under different dc injection currents.

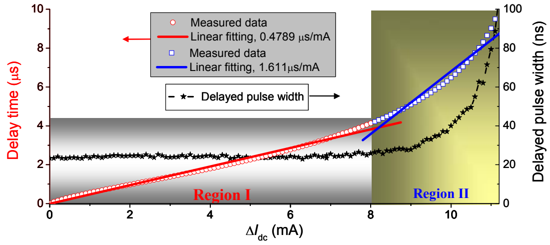


Fig. 4. Dependence of delay time and delayed pulse width on the detuned dc injection current ΔI_{dc} to the control light. The Δf_{cw} on ΔI_{dc} is measured as -0.943 GHz/mA.

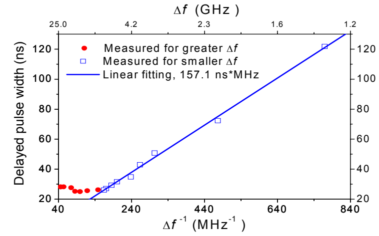


Fig. 5. Dependence of delayed pulse width on the linear modulation depth of the control light.

or of 2 in terms of time with respect to the electric waveform since the pulses are round-trip propagated. Two different delayed pulses of 4.137-μs or 9.498-μs locating in the fall region (I and II) of the electric waveform correspond to two different ΔI_{dc} = 8.00 mA and 11.00 mA, respectively. They both include slight dc levels that are physically attributed to Rayleigh and SpBS. The magnified traces of the delayed pulses by ΔI_{dc} = 0 mA, 0.01 mA 0.60mA, and 1.00 mA are illustrated in Fig. 3(a) providing 0-ns, ~4-ns, ~244-ns or ~420-ns delay time, respectively. Each is Lorentz-like with ~25-ns width. The measured optical spectra for ΔI_{dc} = 0 mA, 1.00 mA and 8.00 mA are plotted in Fig. 3(b). Regardless of the f_{cw} of the control light, the delayed pulses have unchanged optical spectra including strong SBS Stokes and weak Rayleigh and SpBS anti-Stokes, as estimated in Fig. 1(b).

The characterized change of the CW light's f_{cw} on ΔI_{dc} provides a linear slope of -0.943 GHz/mA. The different delay time tuned by ΔI_{dc} is summarized in Fig. 4, which includes two different tunable regions corresponding to two different regions of the electrical waveform [see Fig. 2(b)]. The region I with a maximum modulation depth Δf_1 = ~7.5 GHz denotes a good linear fall region from 0 to 2.068 μs providing a good linearly tunable delay line with a tunable range of $2T_1$ = 4.137 μs and a tunable rate k_1 = 0.4789 μs /mA or -0.5078 μs /GHz. This rate matches well the theoretical value ($k_{10} = -2T_1/\Delta f_1$ = -0.5516 μs/GHz) evaluated from Eq. (3). The modulation in the region II (Δf_2 = ~ 2.9 GHz, T_2 = 2.681 μs) behaves nonlinearly as shown in Fig. 4 that is attributed to the nonlinear fall edge of the electrical waveform as seen in Fig. 2(b). A rough linear fitting gives k_2 = -1.7083 μs /GHz.

The delayed pulse width as a function of ΔI_{dc} is also plotted in Fig. 4. The pulse width scales linearly with the tunable rate k according to Eqs. (3) and (5). In the region II, the k is non-uniformly increased, which determines the nonlinearly-increased pulse width. The delayed pulse width in the region I can not be smaller than the value of τ'' = 25 ns decided by the inverse law [see Eq. (6)] although the width was estimated as τ' = 22 ns according to Eq. (5). It is experimentally confirmed that all the delayed pulse widths in the region I are kept around 23~26 ns, which is almost invariable even if the width of the input pulse signal (τ_0) varies from 30 ns to 320 ns. Meanwhile, we experimentally study the width of the delayed pulse in the region I when various linear modulation depths are introduced to the control light of DFB-2 while the τ_0 is 80 ns. The results are summarized in Fig. 5. When the modulation depth (Δf) exceeds ~6 GHz, the delayed pulse width (τ') are maintained at 25~28 ns. For the lower modulation depth, a good linear dependence of the τ' on Δf^{-1} is observed. The linear slope of $d\tau'/d\Delta f^{-1}$ = 157.1 ns*MHz is got, which agrees excellently with the estimation of $\Delta\nu_B*2T_1$=165.5 ns*MHz according to Eq. (5).

4. Conclusion

We have demonstrated a novel SBS-based fiber optic delay line. By simply tuning the central frequency of the linearly frequency-modulated control light, we have obtained a finest delay time of ~4 ns or random delay time with a maximum linearly tunable range of more than 4 μs. This range can be further improved by designing a longer linear modulation period. Currently, the delay line is limited for a narrow-bandwidth pulse due to the intrinsic SBS linewidth (~40 MHz). It is expectable to realize arbitrary-bandwidth delay line when we adopt multiple control lasers [6] or modulate the dc injection current of the control light by using a Gaussian noise profile [7].

References

[1] G. A. Ball et al., "Programmable fiber optic delay line," *IEEE Photon. Technol. Lett.* **6**, 741-743 (1994).

[2] K.Y. Song et al. "Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering," *Opt. Express* **13**, 82-88 (2005).

[3] Y. Okawachi et al., "Tunable all-optical delays via Brillouin slow light in optical fiber," *Phys. Rev. Lett.* **94**, 153902 (2005).

[4] K. Hotate et al., "Measurement of Brillouin gain spectrum distribution along an optical fiber using a correlation-based technique — Proposal, experiment and simulation," *IEICE Trans. Electron.* **E83-C**, 405-412 (2000).

[5] W. Zou et al., "Correlation-based distributed measurement of SBS-generated dynamic grating spectrum in a polarization-maintaining fiber," in *OFS'19*, post-deadline PD3, Perth, 2008.

[6] M. G. Herraz et al., "Arbitrary-bandwidth Brillouin slow light in optical fibers," *Opt. Express* **14**, 1395-1400 (2006).

[7] Z. Zhu et al., "Broadband SBS slow light in an optical fiber," *J. Lightwave Technol.* **25**, 201-206 (2007).