



Supporting Online Material for
Stored Light in an Optical Fiber via Stimulated Brillouin Scattering

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Supporting Online Material

Materials and Methods

Our experiment setup is shown schematically in Fig. S1. We use two tunable continuous-wave diode lasers operating at wavelengths near $1.55\ \mu\text{m}$, with output frequencies offset by 9.6 GHz. The output intensities are modulated using Mach-Zehnder modulators to create the write, read and data pulses. The modulators are driven by two independent outputs of a pulse-pattern generator. We cascade three Erbium-doped fiber amplifiers to increase the peak power of the write and read pulses. The fiber loop formed by two 3-dB couplers, a 1-km-long single-mode fiber (SMF28e) and a fiber polarization controller is used to remove the weak coherent background and amplified-spontaneous-emission noise. It is a nonlinear transmission element adjusted to pass with high efficiency the write and read pulses and reject the weak background. The write and read pulses enter a 5-m-long highly nonlinear optical fiber – the stored-light medium – where they counterpropagate with respect to the data pulses that enter the fiber via a circulator. The write and read pulses are $\sim 1.5\ \text{ns}$ long, have a nearly rectangular shape as shown in Fig. S2, and have a peak power of $\sim 100\ \text{W}$. They leave the fiber via another circulator and are attenuated before reaching a fast photoreceiver. The data pulses leave the fiber via a circulator and are directed to another photoreceiver. The pulse waveforms are recorded using a high-bandwidth digital sampling oscilloscope. By adjusting the data pattern in the pulse pattern generator, we position the write, read, and pulses so that they interact within the stored-light medium. The strength of the SBS process is maximized by adjusting the polarization state of the data pulses via a polarization controller. The frequency of TL1 (generating the write and read pulses) is tuned to be lower than that of TL2 (generating the data pulses) by the Brillouin frequency shift of about 9.6 GHz.

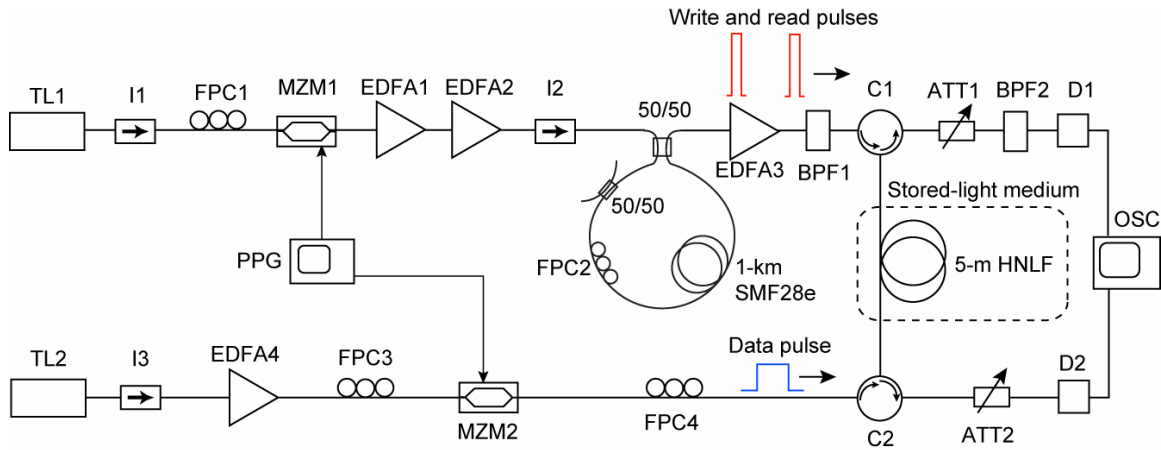


Figure S1: Experiment setup. TL1-2: tunable lasers; I1-3: optical isolators; FPC1-4: fiber polarization controllers; MZM1-2: Mach-Zehnder modulators; PPG: pulse pattern generator; EDFA1-4: Erbium-doped fiber amplifiers; 50/50: 3-dB coupler; BPF1-2: bandpass filters (bandwidth 0.2 nm and 0.06 nm, respectively); C1-2: optical circulators; ATT1-2: tunable attenuators; HNLF: highly nonlinear fiber; D1-2: 13-GHz-bandwidth detectors.

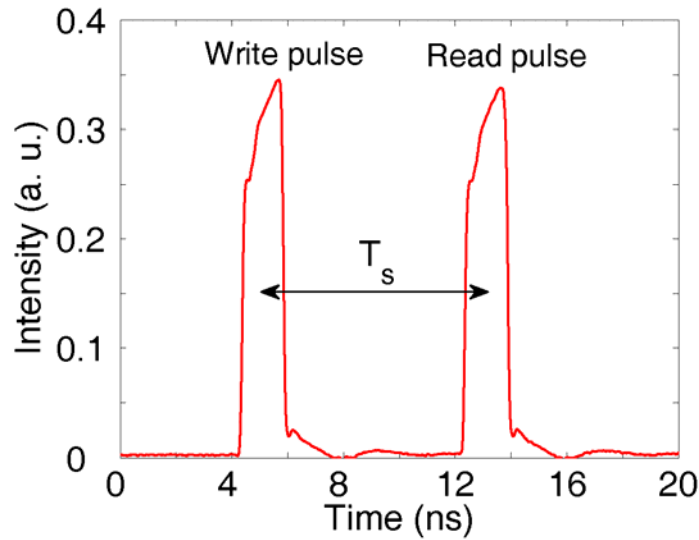


Figure S2: Typical write and read pulses.

The SBS process is described by one-dimensional coupled wave equations involving a forward data field (+z direction), a backward control field (-z direction), and a forward acoustic field. Under the slowly-varying-envelope approximation, the three-wave coupled wave equations are given by (S1):

$$\frac{\partial A_d}{\partial z} + \frac{1}{v_g} \frac{\partial A_d}{\partial t} = -\frac{\eta g_B}{2} A_c Q, \quad (\text{S1a})$$

$$-\frac{\partial A_c}{\partial z} + \frac{1}{v_g} \frac{\partial A_c}{\partial t} = \frac{\eta g_B}{2} A_d Q^*, \quad (\text{S1b})$$

$$2\tau_B \frac{\partial Q}{\partial t} + Q = A_d A_c^*. \quad (\text{S1c})$$

Here, A_d and A_c are slowly-varying electric field envelopes of the data and control (*i.e.*, write and read) pulses, respectively, and Q is related to the slowly-varying amplitude of the acoustic wave ρ by $Q = 2v_a^2 \rho / i\gamma_e \varepsilon_0 \Omega_B \tau_B$, v_a is the acoustic velocity, γ_e is the electrostriction coefficient of the fiber, ε_0 is the vacuum permittivity, Ω_B is the Brillouin frequency shift, τ_B is the acoustic lifetime, v_g is the group velocity of the optical pulses in the fiber, $k_0 = 2\pi/\lambda$, λ is the wavelength of the data or control pulses, $\eta = c\varepsilon_0 n_f / 2$, c is the velocity of light in vacuum, n_f is the modal refractive index of the fiber, and g_B is the SBS intensity gain coefficient. In Eq. (S1c), the spatial derivative of Q describing acoustic-wave propagation is neglected because the acoustic wave is strongly damped (S2).

An analytic solution can be obtained for the special case in which the control pulses are much shorter than the acoustic relaxation time of the medium (S3). The storage and retrieval efficiencies of the data pulses can then be expressed in terms of the “areas” of the write and read pulses, defined as

$$\Theta = \sqrt{g_B v_g n_f \varepsilon_0 c / 16\tau_B} \int A_c(t) dt, \quad (\text{S2})$$

where the integration is carried out over the duration of the pulse. We denote the write-pulse area as Θ_w and the read-pulse area as Θ_r . In the storage process, the data pulse becomes depleted and its amplitude after depletion is given by $A_d(z - v_g t) \cos(\Theta_w)$.

Here, $A_d(z - v_g t)$ is the electric-field envelope of the data pulse expressed in a reference frame moving with the data pulse and, throughout our discussion, we suppress phase factors that do not change our primary predictions. The induced acoustic excitation is given by $A_d(2z) \sin(\Theta_w)$, where we use $2z$ in the argument of A_d to indicate that the spatial extent of the acoustic wave is compressed by a factor of two in comparison to the optical data pulses. In the retrieval process, the acoustic excitation after depletion is given by $A_d(2z) \sin(\Theta_w) \cos(\Theta_r) \exp[-T_s / (2\tau_B)]$ and the retrieved data pulse is given by $A_d(z - v_g t) \sin(\Theta_w) \sin(\Theta_r) \exp[-T_s / (2\tau_B)]$. Based on these expressions, it is seen that ideal storage and retrieval of light pulses can be achieved when $\Theta_w = \Theta_r = (m + 1/2)\pi$, where $m = 0, 1, 2, \dots$. In the experiment, we achieve an area of $\sim\pi/2$ ($m=0$) for both the write and read pulses.

The simulations presented in the paper are obtained by solving Eqs. (S1a)-(S1c) numerically using the method of characteristics (S4). Parameters used in the simulation are: $\lambda = 1.55 \mu\text{m}$, $n_g = 1.5$, $n_f = 1.5$, $A_{\text{eff}} = 11 \mu\text{m}^2$, $\tau_B = 3.4 \text{ ns}$, $g_B = 1.78 \times 10^{-11} \text{ m/W}$. Here, the SBS gain coefficient g_B is inferred from that of bulk silica, scaled by a factor of 0.5 to take into account waveguiding effect in our HNLFF (S5). Data pulses are approximated by a super-Gaussian envelope of form $\exp(-t^{2r})$ with $r = 10$ for rectangular pulses and $r = 2$ for smoothed data pulses. The peak power of the data pulses is 10 mW. The write and read pulses are also approximated by super-Gaussian pulses with $r = 6$ and a pulse width (full width at half maximum) of 1.5 ns. Their peak powers are adjusted around those used experimentally to obtain a pulse area of $\sim\pi/2$, thereby matching the experiment results. We verified that other nonlinear optical effects, such as self- and cross-phase modulation, do not substantially affect our predictions.

References

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