Optics Letters

All-optical flip-flops based on dynamic Brillouin gratings in fibers

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Received 14 April 2017; revised 28 May 2017; accepted 1 June 2017; posted 7 June 2017 (Doc. ID 292711); published 26 June 2017

A method to generate an all-optical flip-flop is proposed and experimentally demonstrated based on dynamic Brillouin gratings (DBGs) in polarization maintaining fibers. In a fiber with sufficiently uniform birefringence, this flip-flop can provide extremely long storage times and ultra-wide bandwidth. The experimental results demonstrate an all-optical flip-flop operation using phase-modulated pulses of 300 ps and a 1 m long DBG. This has led to a time-bandwidth product of ~30, being in this proof-of-concept setup mainly limited by the relatively low bandwidth of the used pulses and the short fiber length.

OCIS codes: (200.4560) Optical data processing; (290.5900) Scattering, stimulated Brillouin; (210.4680) Optical memories; (190.1450) Bistability.

https://doi.org/10.1364/OL.42.002539

Flip-flops are an essential building block in modern electronics. A flip-flop operates bi-stably between two states, depending on some input control signals. In one of the most usual configurations, a flip-flop has two inputs ("set" and "reset") and either one output or, more commonly, two complementary outputs. The output is set to a high level with a positive "set" signal and back to a low level with a positive "reset" signal. Different variants of this structure can be found [1–5].

For many years, photonics has attempted to build all-optical flip-flops using active optical elements and hysteresis processes [1–5]. However, the success of these approaches has been rather limited so far. Typical operation bandwidths have been in the <10–20 GHz range, normally limited by the transition times of the processes used in the lasers/active elements. Additionally, being active, these devices inevitably introduce noise, and turn out to be input power-dependent, which makes them less adaptable to a large variety of scenarios.

Passive approaches have also been proposed in the literature [6–9]. The advantage of passive systems over active ones is that, in principle, they do not add optical noise to the signal and are power-independent. In these approaches, the main idea is to realize extremely long-response-time integrators [7]. An integrator is an optical device whose transfer function is a Heaviside step function. Upon the arrival of a short pulse, the output switches to a high state for a long time (ideally indefinite). Over an arbitrary signal, such a device performs the integral of the electric field of the input signal. Interestingly, such a field integrator can also be operated as a flip-flop: once the output has switched to a high state (with a suitable input pulse), one can easily "reset" its state by launching another short pulse of the same amplitude as the "set" pulse, but with an opposite phase. In this case, the response switches back to zero and remains indefinitely at a low level. Approaches using a resonator [6] and fiber Bragg gratings (FBGs) [7–9] have been reported in the literature. Hybrid (active-passive) approaches incorporating Bragg gratings and active fiber have also been validated [10].

Among the passive approaches, the key performance parameters are the rise time and the integration time. The rise time is simply the time taken to establish the output response above a certain level. The inverse of this value defines the bandwidth of the pulses that the flip-flop can accommodate. The integration time can be defined as the duration of the Heaviside response function of the integrator. In a flip-flop, this value reflects the time over which the output state is preserved with no change in the input. In resonators [6], this parameter is limited by the cavity lifetime of the device, which is related to the losses. In Bragg gratings, this parameter is more related to the FBG length (typically limited to a few tens of centimeters). To achieve a long integration time in FBGs, a very long grating with weak reflectivity is preferred. To make all these approaches easily comparable, the time-bandwidth product is a common figure-of-merit, defined as the storage time multiplied by the bandwidth. State-of-the-art values are ~100 for resonators [6] and >550 for uniform FBGs [7].

In this Letter, a method to develop all-optical flip-flops based on dynamic Brillouin gratings (DBGs) [11] is proposed and experimentally demonstrated in polarization maintaining (PM) fibers. In contrast to existing approaches, this method enables the generation of a very long grating with weak reflectivity using stimulated Brillouin scattering. In this way, extremely long storage times can be achieved with an arbitrarily high bandwidth response.

The proposed method relies on creating a very long, weak DBG along a PM fiber. The grating is dynamically produced by launching two continuous-wave counter-propagating pumps (Pump1 and Pump2) through the opposite sides of a PM fiber [11], as shown in Fig. 1(a). Both pumps must be aligned to the same polarization axis of the fiber. Making the arbitrary choice to align them to the fast axis, their optical frequencies fulfill the condition $f_{\text{Pump2}} = f_{\text{Pump1}} - \nu_B$, where ν_B is the Brillouin frequency along the fast axis of the fiber (typically in the order of 10.8 GHz). These two pumps create a DBG, which acts as an all-optical equivalent of an integrator [12].

The flip-flop output is here set or reset by launching short pulses with a controlled phase into the PM fiber, co-propagating with Pump1, as shown in Fig. 1(a). These pulses must be launched along the slow axis of the PM fiber at the probe frequency $f_{\text{probe}} = (n_{\text{fast}}/n_{\text{slow}}) f_{\text{Pump1}}$ to fulfill the Bragg condition, where n_{fast} and n_{slow} are the fast and slow refractive indices of the PM fiber, respectively. By changing the phase of these pulses, the output of the flip-flop can be set or reset. The flip-flop response can be observed at a frequency $f_R = f_{\text{probe}} - \nu_B$, as shown in Fig. 1(b). Note that the system can also operate if the polarization axes of the pumps and the probe signal are swapped. In such a case, the DBG response appears upshifted in frequency, rather than downshifted.

Figure 2 schematically shows the response of the device when a weak and uniform DBG is generated. The single pulse response of the DBG [Fig. 2(a)], is a truncated Heaviside function (the output is set to a high level from the arrival of the pulse onwards), where the length of the response is limited by the PM fiber length L to a storage time $t_{\text{st}} < 2n_{\text{slow}}L/c_0$. ($c_0$ is the speed of light in vacuum.) To reset the device before the storage time limit [Fig. 2(b)], a second pulse has to be sent into the fiber, with equal amplitude and duration, but an opposite phase compared to the first pulse. The laser coherence time has to be larger than the time difference between the reading pulses. Thus, as a result of the destructive interference between the two out-of-phase reflections, the flip-flop output is set to a low level.

To describe mathematically the operation of the proposed flip-flop, the theory of DBG [12] has to consider the interactions between the four involved optical waves and one acoustic wave. The writing and reading of a DBG can be described by the following system of coupled equations:

$$\frac{\partial A_{\text{Pump1}}}{\partial z} + \frac{n_{\text{fast}}}{c_0}\frac{\partial A_{\text{Pump1}}}{\partial t} = i\frac{1}{2} g_2 A_{\text{Pump2}}\rho - \frac{\alpha}{2} A_{\text{Pump1}}, \quad \textbf{(1.a)}$$

$$\frac{\partial A_{\text{Pump2}}}{\partial z} - \frac{n_{\text{fast}}}{c_0}\frac{\partial A_{\text{Pump2}}}{\partial t} = -i\frac{1}{2} g_2 A_{\text{Pump2}}\rho^* + \frac{\alpha}{2} A_{\text{Pump2}}, \quad \textbf{(1.b)}$$

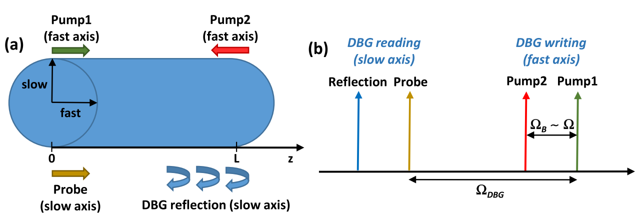

Fig. 1. Generation and reading of a DBG in a PM fiber. (a) Direction of propagation and polarization axes of the four interacting optical waves. (b) Frequency distribution of the optical waves.

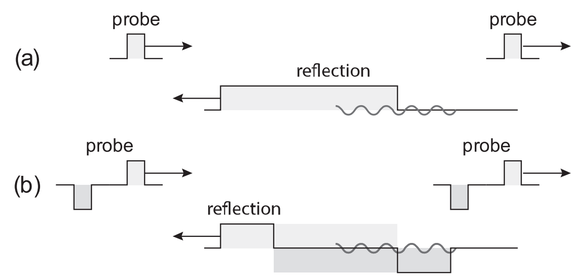

Fig. 2. Working principle of the proposed all-optical flip-flop using DBGs. (a) Flip-flop output is set with an incoming pulse. This causes a step response at the output of a long, weak DBG tuned at the working wavelength. (b) Output can be switched back to a low level by using a second probe pulse with the opposite phase. The high level at the output is kept along the time lapse between the two pulses.

$$\frac{\partial \rho}{\partial t} + \Gamma_A \rho = i g_1 A_{\text{Pump1}} A^*_{\text{Pump2}}, \quad \textbf{(1.c)}$$

$$\frac{\partial A_{\text{Probe}}}{\partial z} + \frac{n_{\text{slow}}}{c_0}\frac{\partial A_{\text{Probe}}}{\partial t} = i g_2 A_R \rho e^{i\Delta k z} - \frac{\alpha}{2} A_{\text{Probe}}, \quad \textbf{(1.d)}$$

$$\frac{\partial A_R}{\partial z} - \frac{n_{\text{slow}}}{c_0}\frac{\partial A_R}{\partial t} = -i g_2 A_{\text{Probe}} \rho^* e^{-i\Delta k z} + \frac{\alpha}{2} A_R, \quad \textbf{(1.e)}$$

where A_{Pump1}, A_{Pump2}, A_{Probe}, and A_R are the amplitudes of the optical fields of Pump1, Pump2, probe, and reflection, respectively; ρ is the acoustic wave amplitude; g_1 and g_2 are the electrostrictive and elasto-optic coupling coefficients; Δk is the phase mismatch among the pumps and probe pulses; and $\Gamma_A = i(\Omega_B^2 - \Omega^2 - i\Omega\Gamma_B)/2\Omega$ is the frequency detuning factor. (Ω_B and Γ_B are the Brillouin frequency and spectral linewidth.) Equations (1.d) and (1.e) represent the DBG reading process and can be simplified under the following conditions: (1) negligible depletion or amplification of Pump1 and Pump2, (2) steady-state conditions for the DBG writing (i.e., neglecting the acoustic wave transit time), (3) negligible optical losses along the fiber, and (4) $A_R \ll A_{\text{Probe}}$. These conditions can be easily satisfied, so that the DBG reading can be safely described as

$$\frac{\partial A_{\text{Probe}}}{\partial z} = i\kappa(z) A_R e^{i\Delta k(z) z} \approx 0, \quad \textbf{(2.a)}$$

$$\frac{\partial A_R}{\partial z} = -i\kappa^*(z) A_{\text{Probe}} e^{-i\Delta k(z) z}, \quad \textbf{(2.b)}$$

where the coupling coefficient $\kappa(z)$ is limited in the range $z = [0, L]$, L being the DBG length, so that

$$\kappa(z) = i(g_1 g_2 / 2\Gamma_A) A_{\text{Pump1}} A^*_{\text{Pump2}} \operatorname{rect}(z/L), \quad \textbf{(3)}$$

where $\operatorname{rect}(x) = 1$ for $x \in [0, 1]$, and $\operatorname{rect}(x) = 0$ for $x \notin [0, 1]$.

After integrating Eq. (3), the transfer function of the DBG reflection can be written as

$$T_R(\omega_{\text{Probe}}) \equiv \frac{A_R(\omega_{\text{Probe}} - \omega, z = 0)}{A_{\text{Probe}}(\omega_{\text{Probe}})} = i\int_{-\infty}^{\infty} \kappa^*(z) e^{-i\Delta k(z) z} \mathrm{d}z, \quad \textbf{(4)}$$

where $\Delta k \approx -2n[(\omega_{\text{Probe}} - \omega_{\text{Pump1}}) - \Omega_{\text{DBG}}]/c_0$ and $z = ct/2n$, being $n = (n_{\text{slow}} + n_{\text{fast}})/2$ and $\Omega_{\text{DBG}} = \omega_{\text{Pump1}}(n_{\text{slow}} - n_{\text{fast}})/n$. Considering that the local

DBG frequency $\Omega_{\mathrm{DBG}}(z)$ can be expressed as the sum of a constant mean value $\langle\Omega_{\mathrm{DBG}}\rangle$ and local changes $\Delta\Omega_{\mathrm{DBG}}(z)$, and that the DBG is read at its peak frequency, so that $\Delta\omega_{\mathrm{Probe}} = (\omega_{\mathrm{Probe}} - \omega_{\mathrm{Pump1}}) - \langle\Omega_{\mathrm{DBG}}\rangle$, we can write

$$T_R(\Delta\omega_{\mathrm{Probe}}) = i\frac{c_0}{2n}\int_{-\infty}^{\infty}\kappa^*(c_0t/2n)e^{-it\Delta\Omega_{\mathrm{DBG}}(c_0t/2n)}e^{it\Delta\omega_{\mathrm{Probe}}}\mathrm{d}t, \tag{5}$$

which can be seen as the Fourier transform of the impulse response of the DBG. Then, the BGS impulse response can be obtained by inverse Fourier transform so that

$$h_R(t) = \frac{c_0}{2n}\kappa^*(c_0t/2n)\exp[-it\Delta\Omega_{\mathrm{DBG}}(c_0t/2n)]. \tag{6}$$

Thus, in case there are no birefringence fluctuations (i.e., $\Delta\Omega_{\mathrm{DBG}} = 0$), the DBG impulse response becomes

$$h_R(t) = \frac{c_0}{2n}\kappa^*(c_0t/2n) \propto C\,\mathrm{rect}\left(\frac{c_0t}{2nL}\right), \tag{7}$$

where C is a constant. Then $h_R(t)$ is real, constant, and maximum when $\Delta\Omega_{\mathrm{DBG}} = \Delta\Omega_B = 0$ over a temporal length $(0 < t < 2nL/c_0)$. In essence, this is a step function time-limited to $2nL/c_0$, i.e., the storage time limit t_{st} of the flip-flop. Considering the typical lengths of the PM fibers used in DBGs, $2nL/c_0$ might reach microseconds, which is extremely long for an optical flip-flop. If the setting and resetting pulses are very short, the response of the flip-flop can be written as

$$\begin{aligned} v_{\mathrm{FF}}(t) &= h_R(t) - h_R(t-\Delta\tau) \\ &\propto C[\mathrm{rect}(c_0t/2n) - \mathrm{rect}(c_0(t-\Delta\tau)/2n)], \end{aligned} \tag{8}$$

where $\Delta\tau$ is the time difference between pulses.

It must be noted that the subtraction of the rectangular functions in Eq. (8) leads to a response given by two components, as depicted in Fig. 2(b): a first response from $t = 0$ until $t = \Delta\tau$, corresponding to the signal of interest, and a second component occurring from $t = 2nL/c_0$ until $t = 2nL/c_0 + \Delta\tau$. This second echo can be electrically suppressed, so that it can be discarded from the flip-flop operation.

Note than $\kappa(z)$ defines the local reflectivity of the grating, which has a maximum (at the peak frequency) equal to [13]

$$r_{\max} = \tanh^2\left(\frac{g_B\sqrt{P_{\mathrm{Pump1}}P_{\mathrm{Pump2}}}\Delta l}{2A_{\mathrm{eff}}}\right), \tag{9}$$

where g_B is the Brillouin coefficient, $P_{\mathrm{Pump1,2}}$ are the powers of Pump1 and Pump2, A_{eff} is the effective area, and Δl is the probe pulse length.

Figure 3 shows the experimental setup used to demonstrate the DBG-based flip-flop operation. The light from a distributed feedback (DFB) laser, at 1551 nm, is split into two branches to produce the counter-propagating pumps. The light in the upper branch is used to generate Pump2 at the laser nominal wavelength, which is amplified by an erbium-doped optical amplifier (EDFA) to ~25 dBm. This pump is launched into the fast polarization axis of a 1 m long Panda PM fiber. In the lower branch, Pump1 is obtained by intensity modulating the light using an electro-optic modulator (EOM) in carrier-suppression mode and driven by a microwave frequency, which allows precise control of the frequency offset between pumps. Using a polarization beam combiner (PBC) after an EDFA, Pump1 is also launched into the fast axis of the PM fiber with a power of ~25 dBm. Note that the two modulation sidebands in Pump1 generate two DBGs propagating in opposite directions. Either grating can be selectively used since they both satisfy a distinct Bragg condition.

To change the state of the flip-flop, short pulses with opposite phases are used. These pulses are generated using another DFB laser, whose optical frequency is tuned to match the resonant frequency of one of the generated DBGs, but along the slow axis of the PM fiber. Gaussian-like-shaped pulses of 300 ps fullwidth at half-maximum are obtained using intensity and phase modulators, thus producing the set and reset pulses for the flip-flop with a relative π-phase shift. These pulses are amplified by an EDFA and sent into the slow axis of the PM fiber through the PBC. The signal reflected from the DBG (also in the slow axis) is selected by a 10 GHz FBG filter (in reflection) and sent into a photodetector connected to a 4 GHz oscilloscope. Considering the experimental conditions, Eq. (9) indicates that the created DBG has a maximum reflectivity of $5.63\cdot10^{-6}$ (for 300 ps pulses, $\Delta l = 6$ cm).

Measurements are obtained with and without the phase modulation of the second pulse. Figure 4 shows the experimental results obtained with pulse separations of 3.5 [Fig. 4(a)], 5 [Fig. 4(b)], and 6.5 ns [Fig. 4(c)]. The first section of the measured signals corresponds to the reflection of the first pulse, while the second section shows the destructive (red curves) or constructive (gray curves) interference of the two reflections. The results indicate that when the phase modulation is turned off, the two reflections sum up in phase, giving an amplitude proportional to the integral of the two pulses (i.e., four times the intensity response of a single pulse). However, applying a π-phase shift to the second pulse (i.e., for resetting the flip-flop), the reflections mix on the photodetection with opposite phases, thus mutually canceling out and showing the expected flip-flop operation. The results show a time-bandwidth product of ~30, being in this case mainly limited by the short PM fiber and a low bandwidth of the pulses used in this proof-of-concept.

Finally, Fig. 5 shows the amplitude response of the system as a function of the spectral detuning between the probe pulses and the DBG Bragg resonance (using 300 ps pulses separated by 5 ns). It shows that when the two pulses are perfectly centered

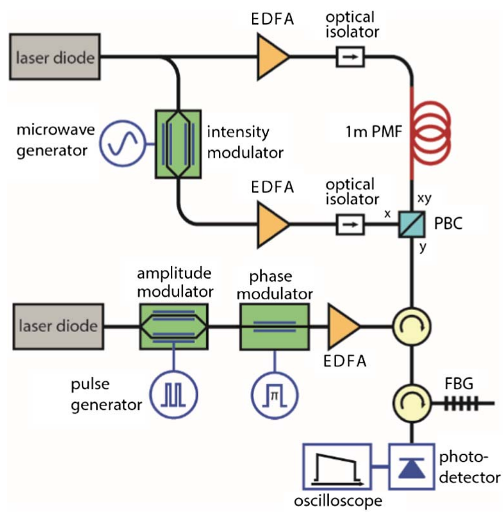

Fig. 3. Proof-of-concept setup.

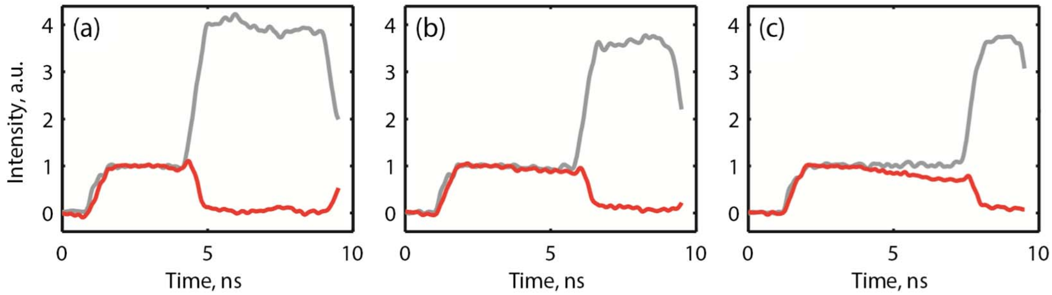

Fig. 4. Experimental demonstration of an all-optical flip-flop using a 1 m long DBG. The flip-flop operation (red lines) resulting from out-of-phase pulses is compared with the integration (gray) resulting from two in-phase pulses. The pulse separation is (a) 3.5, (b) 5, and (c) 6.5 ns.

at the DBG peak, the out-of-phase reflections fully mutually cancel out, resetting the flip-flop. This behavior is independent of the pulse duration and pulse separation. However, when probe pulses are detuned from the DBG peak by $\Delta\omega$, a phase mismatch equal to $\Delta\omega\Delta\tau$ is added between the two reflections, resulting in a nonperfect cancellation of the two reflections. This means that the system behaves as a flip-flop only for $\Delta\omega = 0$.

This spectral behavior implies that, to achieve a perfect flip-flop operation, a fiber with a uniform birefringence profile is required. Longitudinal variations of the birefringence unavoidably induce local spectral detuning of the DBG ($\Delta\omega \neq 0$), introducing a phase mismatch that could impair the flip-flop operation. To secure a storage time t_{st}, a uniform birefringence along a length $L > t_{st}c_0/2n$ is ideally required, while the impact of enviromental conditions (e.g., strain or temperature) on the fiber birefringence must be reduced.

In conclusion, a method to achieve all-optical flip-flop operation has been proposed and experimentally demonstrated using a DBG. The proposed flip-flop scheme could ideally provide extremely long storage times when compared to reported passive schemes, being fundamentally limited only by the fiber length and its birefringence uniformity. No physical limitations can be envisaged in the rise time which, in principle, is similar to passive FBG-based flip-flops (i.e., as fast as 6 ps [8]). However, practical limitations could exist due to polarization coupling effects and non-ideal filtering of Pump2. In this case, overlapping between reflection and Pump2 must be avoided so that the real bandwidth of the flip-flop turns out to be limited by the fiber birefringence to $\Omega_{DBG/2\pi}$, being 43.6 GHz in this experiment and defining a rise time of ~23 ps. Another limitation is imposed by real variations of the birefringence along long PM fibers. According to today's technology, usual birefringence nonuniformities along PM fibers limits the storage time to ~10 ns (~1 m of fiber). To achieve microsecond storage times (~100 m of fiber), ~2 orders of magnitude improvement in the uniformity of the fiber birefringence would be required.

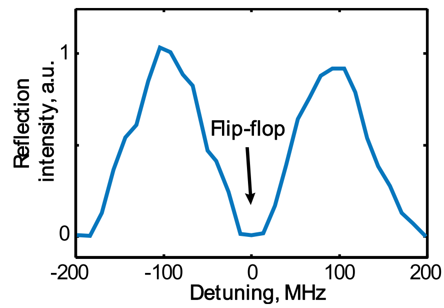

Fig. 5. Output intensity of the device for two 300 ps pulses separated by 5 ns, as a function of the frequency detuning from the DBG peak. The expected flip-flop operation occurs at zero detuning only.

Funding. Swiss National Science Foundation (159897); H2020 European Research Council (ERC) (307441); Ministerio de Economía y Competitividad (MINECO) Ramón y Cajal (TEC2013-45265-R, TEC2015-71127-C2-2-R); European Commission (EC) (MSCA-ITN-ETN-722509); Consejería de Educación, Juventud y Deporte, Comunidad de Madrid SINFOTON-CM Program (S2013/MIT-2790).

REFERENCES

1. M. T. Hill, H. de Waardt, G. D. Khoe, and H. J. S. Dorren, IEEE J. Quantum Electron. **37**, 405 (2001).
2. M. T. Hill, H. J. S. Dorren, T. de Vries, X. J. M. Leijtens, J. H. den Besten, B. Smalbrugge, Y.-S. Oei, H. Binsma, G.-D. Khoe, and M. K. Smit, Nature **432**, 206 (2004).
3. K. Huybrechts, G. Morthier, and R. Baets, Opt. Express **16**, 11405 (2008).
4. A. Malacarne, J. Wang, Y. Zhang, A. D. Barman, G. Berrettini, L. Potì, and A. Bogoni, IEEE Photon. Technol. Lett. **14**, 803 (2008).
5. M. Takenaka, M. Raburn, and Y. Nakano, IEEE Photon. Technol. Lett. **17**, 968 (2005).
6. M. Ferrera, Y. Park, L. Razzari, B. E. Little, S. T. Chu, R. Morandotti, D. J. Moss, and J. Azaña, Nat. Commun. **1**, 29 (2010).
7. M. H. Asghari and J. Azana, IEEE Photon. Technol. Lett. **23**, 209 (2011).
8. Y. Park, T.-J. Ahn, Y. Dai, J. Yao, and J. Azaña, Opt. Express **16**, 17817 (2008).
9. M. A. Preciado and M. A. Muriel, Opt. Lett. **33**, 1348 (2008).
10. R. Slavík, Y. Park, N. Ayotte, S. Doucet, T.-J. Ahn, S. LaRochelle, and J. Azaña, Opt. Express **16**, 18202 (2008).
11. K. Y. Song, W. Zou, Z. He, and K. Hotate, Opt. Lett. **33**, 926 (2008).
12. M. Santagiustina, S. Chin, N. Primerov, L. Ursini, and L. Thévenaz, Sci. Rep. **3**, 1594 (2013).
13. K. Y. Song, K. Hotate, W. Zou, and Z. He, J. Lightwave Technol. **PP**, 1 (2016).