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

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A method to generate an all-optical flip-flop is proposed and experimentally demonstrated based on dynamic Brillouin gratings in polarization maintaining fibers. In a fiber with sufficiently uniform birefringence, this flip-flop can provide extremely long storage times and ultra-wide bandwidth. Experimental results demonstrate all-optical flip-flop operation using phase-modulated pulses of 300 ps and a 1 m-long dynamic Brillouin grating. 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.

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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 usually 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. However, in broad terms, the explained paradigm is preserved in the vast majority of systems performing this operation: the flip-flop circuit remains in a particular output state indefinitely until some variation in the inputs changes its output state [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, mainly because the conditions for bi-stable operation remain highly dependent on the bit-rate and the required optical powers. 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. Although all these approaches attract strong scientific interest, they remain unexplored in terms of real deployment.

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 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 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 opposite phase. In that case, the response switches back to zero and remains indefinitely at low level. Hence, a photonic electric field integrator with a suitably long response time can be easily turned into a flip-flop by using proper control signals. 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 obtained from the impulse response of the device. These key 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, i.e. the time lapse between the onset of the Heaviside impulse response and the decay of the output signal below a certain level. The integration time should be ideally infinite. 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 cm). To achieve a long

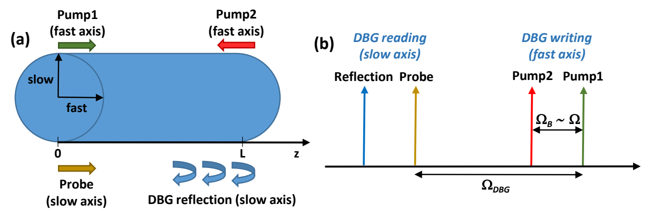

Fig. 1. Generation and reading of a DBG in a PM fiber. (a) Direction of propagation and polarization axes of the 4 interacting optical waves. (b) Frequency distribution of the optical waves.

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. Contrarily to existing approaches, this method enables the generation of a very long grating with weak reflectivity using stimulated Brillouin scattering. 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 fulfil the condition: $f_{Pump2} = f_{Pump1} - \nu_B$, 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 controlled phase into the PM fiber, co-propagating with Pump1, as shown in Fig. 1(a). For proper operation these pulses must be launched along the orthogonal slow axis of the PM fiber at the probe frequency $f_{probe} = (n_{fast}/n_{slow})f_{Pump1}$ to fulfil 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 $f_R = f_{probe} - \nu_B$, as shown in Fig. 1(b). Note that the system can operate in the same manner if the polarization axes of the pumps and the probe signal are swapped. In such a case, the DBG response appears upshifted in frequency (with respect to the pumps) rather than down-shifted.

Figure 2 schematically shows the response of the device when a weak and completely uniform Brillouin grating is generated. When the grating is probed with a single pulse (Fig. 2(a)), the response corresponds to 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 $t_{st} < 2\ n_{slow}L/c_0$ (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 opposite phase compared to the first pulse. The main requirement for the laser source is that its coherence time has to be larger than the time difference between reading pulses. Thus, as a result of the destructive interference between the two out-of-phase reflections, the flip-flop output is set to low level.

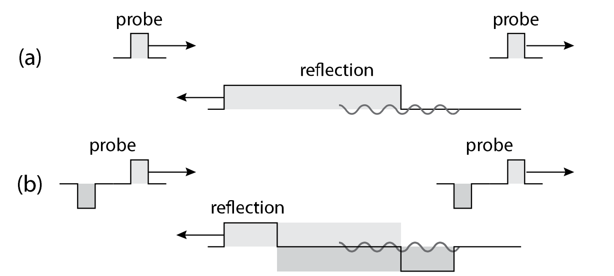

Fig. 2. Working principle of the proposed all-optical flip-flop using DBGs. (a) The flip-flop output is set with an incoming pulse. This causes a step response at the output of a long, weak DBG tuned at the working wavelength. The storage time limit is given by the fiber length. (b) The output can be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

In order to describe mathematically the operation of the proposed flip-flop, the theory of DBG [12] has to consider the interactions between the 4 involved optical waves and 1 acoustic wave. In particular the writing and reading of a DBG can be described by the following system of coupled equations:

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

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

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

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

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

where A_{Pump1}, A_{Pump2}, A_{Probe} and A_R are the amplitudes of the optical field 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 pumps and probe pulses; and $\Gamma_A = i(\Omega^2_B - \Omega^2 - i\Omega\Gamma_B) / 2\Omega$ is the complex frequency detuning factor (Ω_B and Γ_B are the Brillouin angular frequency and spectral linewidth). Equations (1.d) and (1.e) represent the DBG reading process and can be mathematically simplified under the following conditions: *i)* negligible depletion or amplification of Pump1 and Pump2, *ii)* steady-state conditions for the DBG writing (i.e. neglecting the transit time for acoustic wave activation), *iii)* negligible optical losses along the fiber and *iv)* $A_R << A_{Probe}$. These conditions can be easily satisfied by any well-designed DBG system, so that the DBG reading can be safely described as:

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

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

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

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

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

After integrating Eqs. (2), the transfer function of the dynamic Brillouin grating reflection can be written as:

$$T_R\left(\omega_{Probe}\right) \equiv \frac{A_R\left(\omega_{Probe}-\omega, z=0\right)}{A_{Probe}\left(\omega_{Probe}\right)} = i\int_{-\infty}^{\infty} \kappa^*\left(z\right) e^{-i\Delta k(z)z} dz \; . \quad \textbf{(4)}$$

Considering $\Delta k \approx -2n[(\omega_{Probe} - \omega_{Pump1}) - \Omega_{DBG}]/c_0$ and $z = ct/2n$, and defining the average refractive index as $n = (n_{slow} + n_{fast})/2$ and the angular frequency of the DBG as $\Omega_{DBG} = \omega_{Pump1}(n_{slow} - n_{fast})/n$, Eq. (4) can be written as:

$$T_R(\omega_{Probe}) = i\frac{c_0}{2n}\int_{-\infty}^{\infty} \kappa^*(c_0 t/2n) e^{-it\left[\Omega_{DBG}(c_0 t/2n)+(\omega_{Probe}-\omega_{Pump1})\right]} dt \quad \textbf{(5)}$$

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

$$T_R\left(\Delta\omega_{Probe}\right) = i\frac{c_0}{2n}\int_{-\infty}^{\infty} \kappa^*\left(c_0 t/2n\right) e^{-it\Delta\Omega_{DBG}(c_0 t/2n)} e^{it\Delta\omega_{Probe}} dt \; , \quad \textbf{(6)}$$

which can be seen as the Fourier transform of the impulse response of the DBG. Therefore, the impulse response of the DBG can be obtained by applying the inverse Fourier transform, so that:

$$h_R\left(t\right) = \frac{c_0}{2n}\kappa^*\left(c_0 t/2n\right)\exp\left[-it\Delta\Omega_{DBG}\left(c_0 t/2n\right)\right]. \qquad \textbf{(7)}$$

In case there are no birefringence fluctuations (i.e. $\Delta\Omega_{DBG} = 0$), the impulse response of the DBG can be written as:

$$h_R\left(t\right) = \frac{c_0}{2n}\kappa^*\left(c_0 t/2n\right) \propto C\, rect\left(\frac{c_0 t}{2nL}\right), \qquad \textbf{(8)}$$

where C is a constant. Then, $h_R(t)$ is real, constant and maximum when $\Delta\Omega_{DBG} = \Delta\Omega_B = 0$ 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 typical lengths of 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 (so that they can be approximated as delta functions), then the response of the flip-flop can be written as

$$\begin{aligned} v_{FF}\left(t\right) &= h_R\left(t\right) - h_R\left(t-\Delta\tau\right) \\ &\propto C\left[rect\left(c_0 t/2n\right) - rect\left(c_0(t-\Delta\tau)/2n\right)\right], \end{aligned} \qquad \textbf{(9)}$$

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

It must be noted that the subtraction of the rectangular functions in Eq. (9) leads to a response given by two components, as depicted in Fig. 2b: a first response from the arrival of the first pulse until the arrival of the second one (i.e. 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]:

$$r_{\max} = \tanh^2\left(\frac{g_B\sqrt{P_{Pump1}P_{Pump2}}\,\Delta l}{2A_{eff}}\right), \qquad \textbf{(10)}$$

where g_B is the Brillouin coefficient, $P_{Pump1,2}$ 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 distinct branches using a PM splitter to produce the two counter-propagating pumps for the DBG generation. 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 a 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 satisfying a distinct Bragg condition.

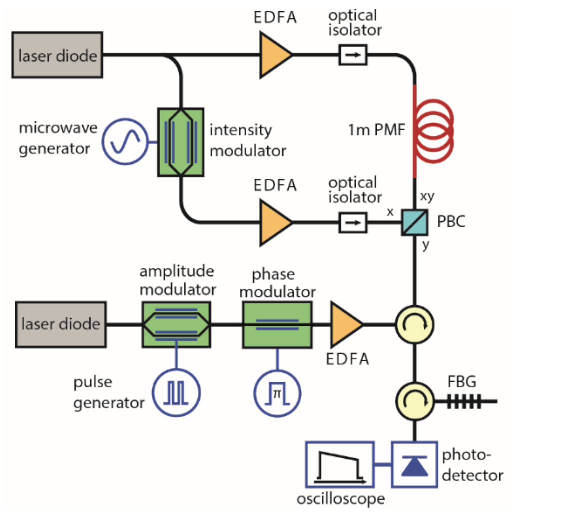

Fig. 3. Proof-of-concept setup for the generation of an all-optical flip flop based on a dynamic Brillouin grating.

In order to change the state of the flip-flop, short pulses with opposite phases are used. Those 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 full-width 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 (operating in reflection) and sent into a photodetector connected to a fast oscilloscope (4 GHz bandwidth). Considering the experimental conditions, Eq. (10) indicates that the created DBG has a maximum reflectivity $5.63 \cdot 10^{-6}$ (for 300 ps pulses, $\Delta l = 6$ cm).

Measurements have been obtained varying the pulse separation between 3.5 ns up to 6.5 ns, with and without the phase modulation of the second pulse. Figure 4 shows the experimental results obtained with pulse separations of 3.5 ns (Fig. 4a), 5 ns (Fig. 4b) and 6.5 ns (Fig. 4c). The first section of the measured time-domain signals corresponds to the reflection of the first pulse, while the second section shows the destructive (red curves) or constructive (grey curves) interference of the two reflections. Results indicate that when the phase modulation is turned off, the two reflections sum up in phase, leading to a constructive interference, and giving an amplitude proportional to the integral of the two pulses (i.e. 4 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

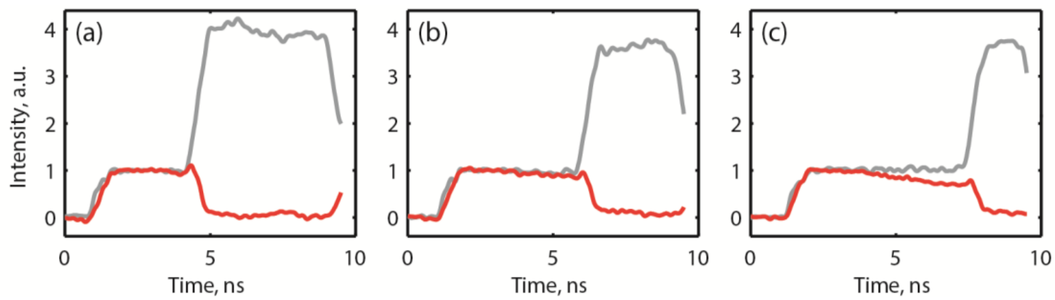

Fig. 4. Experimental demonstration of an all-optical flip-flop using a 1 m-long DBG. The flip-flop operation (red lines) resulting from out-of-phase pulses is compared with the integration (grey) resulting from two in-phase pulses. The pulse separation is: (a) 3.5 ns, (b) 5 ns, and (c) 6.5 ns.

reflections mix on the photo-detection with opposite phases, thus mutually cancelling out and showing the expected flip-flop operation (red curves). Results show a time-bandwidth product of ~30, being in this case mainly limited by the short PM fiber and low bandwidth of the pulses used in this proof-of-concept experiment.

Finally, Fig. 5 shows the amplitude response of the system as a function of the spectral detuning between 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 at the DBG peak, the out-of-phase reflections fully mutually cancel out, resulting in a complete reset of 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 non-perfect cancellation of the two reflections. This means that the system behaves as a flip-flop only for $\Delta\omega = 0$. Interestingly, for the case of using two out-of-phase pulses detuned at $\Delta\omega = \pi/\Delta\tau$ (and all odd multiples), reflections turn out to be in phase, so that the output signal becomes the integral of the field amplitude of the pulses.

This spectral behavior implies that, to achieve a perfect flip-flop operation, a fiber with 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 of the system, which in principle is similar to those passive flip-flops based on FBGs (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 that 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 $2\pi\Omega_{DBG}$, 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 non-uniformities along PM fibers limit 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.

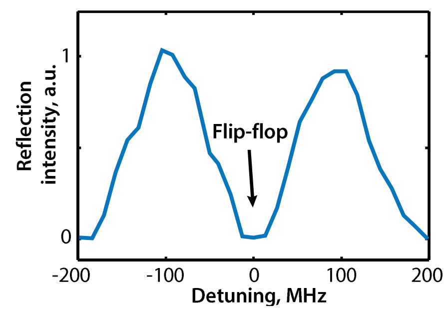

Fig. 5. Output intensity of the device for two 300 ps pulses separated by 5 ns, as a function of the frequency detuning from the DBG peak. The expected flip-flop operation occurs at zero detuning only, while the system integrates the field amplitude of the pulses at $\Delta\omega = \pi/\Delta\tau$.

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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. Lightw. Technol. PP(99), 1 (2016).