High-order passive photonic temporal integrators

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We experimentally demonstrate, for the first time to our knowledge, an ultrafast photonic high-order (second-order) complex-field temporal integrator. The demonstrated device uses a single apodized uniform-period fiber Bragg grating (FBG), and it is based on a general FBG design approach for implementing optimized arbitrary-order photonic passive temporal integrators. Using this same design approach, we also fabricate and test a first-order passive temporal integrator offering an energetic-efficiency improvement of more than 1 order of magnitude as compared with previously reported passive first-order temporal integrators. Accurate and efficient first- and second-order temporal integrations of ultrafast complex-field optical signals (with temporal features as fast as $\sim$2.5 ps) are successfully demonstrated using the fabricated FBG devices.

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An Nth-order temporal integrator (where $N = 1,2,3\ldots$ refers to the integration order) is a device that calculates the Nth cumulative time integral of an input signal. Temporal integrators are fundamental basic blocks in many signal processing operations of interest, e.g., in computing, control, and communication networks [1]. As compared with their electronic counterparts, photonic temporal integrators [2–10] can provide much higher operation bandwidths, i.e., higher processing speeds. Photonic first-order temporal integrators have already been proposed for various interesting applications, including ultrafast pulse shaping [2,3] and all-optical memories [4]. Higher-order integrators are also key building blocks in a large number of signal processing circuits [1]. A relevant example of application of these devices is that of computing systems devoted to solving ordinary differential equations (ODEs). Linear ODEs can be solved in real time using a suitable combination of first and high-order integrators, adders, and multipliers. Realizing these operations all-optically would translate into processing speeds well beyond the reach of present electronic digital or analog computing solutions [3].

All the previously demonstrated integrators (using a fiber Bragg grating (FBG)-based active resonant cavity design [3] and a passive filtering solution based on a single uniform FBG [5]) can provide only the first cumulative time integral (i.e., first-order integrators). In principle, an Nth-order photonic integrator could be implemented by concatenating in series N first-order photonic integrators [2,7,8]. However, this would lead to a design in which the implementation complexity is increased for higher integration orders, which would also translate into a degraded device performance, e.g., in terms of energetic efficiency. Some passive filtering designs have been recently proposed for implementing an arbitrary-order photonic temporal integrator using a single FBG device [9,10]. An interesting solution is based on using a single weak-coupling uniform-period FBG operated in reflection with a customized amplitude-only grating apodization profile according to the target integration order [9]. The FBG-based first-order photonic integrator demonstrated in [5] can be considered as a particular case of this generalized design. As a main advantage, this general solution can offer processing speeds in the tetrahertz range, limited only by the grating's reflection bandwidth that can be practically fabricated. The main drawback of the FBG design proposed in [9] is that it necessarily requires the use of FBGs with peak reflectivities $<10-15\%$; as a result, this solution suffers from a low energetic efficiency, which makes practically challenging the experimental implementation of this idea for high-order photonic integration. To solve this fundamental drawback, we have recently proposed an improved FBG design for ultrafast passive first and high-order photonic integration with fully optimized energetic efficiencies [10]. The proposed solution is based on a single high-reflectivity (peak reflectivity of $\sim$100%) FBG providing a temporal impulse response that approximates that of the targeted ideal Nth-order photonic integrator, in which the grating profile is designed using an inverse-scattering FBG synthesis algorithm [11].

In this Letter, we report what we believe to be the first experimental demonstration of an ultrafast photonic high-order (second-order) complex-field integrator. This realization has been possible by use of the optimized FBG integrator design approach proposed in [10]. Moreover, we have also implemented an improved ultrafast photonic first-order integrator based on this same FBG design strategy and have experimentally achieved an $\sim$13-fold increase in terms of energetic efficiency as compared with the previously demonstrated passive (FBG) first-order temporal integrator [5]. Accurate first and second-order temporal

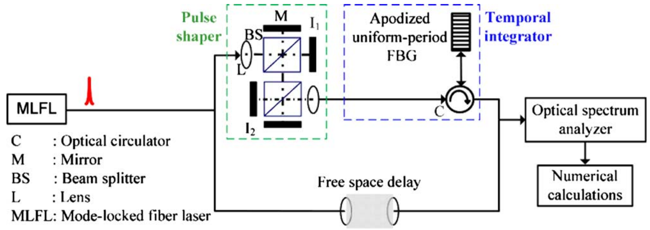

Fig. 1. (Color online) Experimental setup for temporal characterization of the fabricated FBG-based first- and second-order ultrafast photonic temporal integrators.

integrations of ultrafast complex-field optical signals (with time features as fast as ~2.5 ps) are thus successfully demonstrated.

Let us assume an arbitrary optical signal that is launched at the input of an ideal Nth-order optical integrator ($N=1,2,3\ldots$). The complex envelope of the output optical signal from this integrator is proportional to the Nth-time cumulative integral of the input complex envelope [1]. This functionality can be implemented over a finite time interval $0 \le t \le T_h$ (limited operation time window of the integrator) using a single passive optical filter providing a baseband temporal impulse response $h_N(t)$ [9],

$$h_N(t) \propto t^{N-1} \times \prod \left(\frac{t - T_h/2}{T_h} \right), \qquad (1)$$

where the function $\Pi((t-T_h/2)/T_h)$ is the square function of duration T_h, centered at $T_h/2$; t is the time variable; and the symbol $\propto$ indicates proportionality. Thus, a first-order [second-order] passive photonic integrator should exhibit a uniform [linear] temporal impulse response profile over the prescribed operation time window. To implement an efficient FBG-based Nth-order photonic integrator, we proposed using a layer-peeling synthesis algorithm [11] to synthesize the grating profile of a high-reflectivity (ideally 100% peak reflectivity) FBG providing the corresponding temporal impulse response, as defined by Eq. (1) [10]. First- and second-order photonic integrators are here experimentally demonstrated based on this optimized FBG approach.

For all of the designs in this Letter, we targeted an integration time window $T_h = 60$ ps. Our simulations showed that a grating length of 2.5 cm (assuming $n_{\mathrm{eff}} = 1.452$) was long enough to achieve an FBG peak reflectivity of $\approx 100\%$ while avoiding the need for any grating period variation (chirp or discrete phase shifts) in the obtained FBG profile. The insets of Figs. 2(a) and 2(b) show the designed amplitude-only apodization profiles for first- (assuming a uniform grating period of $\Lambda = 535.68$ nm) and second ($\Lambda = 535.39$ nm)-order integrators, respectively, as obtained from the layer peeling synthesis algorithm. The designed FBG profiles were then fabricated in a photosensitive fiber by a frequency-doubled argon-ion laser operating at 244 nm using a 15-cm-long uniform phase mask. In each case, the desired amplitude-only grating apodization profile was achieved by controlling the laser beam scanning velocity while maintaining a constant laser power. The measured reflection amplitude spectral responses of the fabricated FBGs for first- and second-order temporal integrators are plotted in the inset of the Figs. 2(a) and 2(b), confirming that we achieved the desired high peak reflectivities ($\approx 98.7\%$ and $\approx 97.4\%$, respectively).

The setup used for our experiments is shown in Fig. 1. In particular, a Fourier transform spectral interferometry (FTSI) technique [5] was used for complex-field optical signal characterization. We first measured the ultrashort temporal pulse responses of the fabricated FBGs. For this purpose, we used transform-limited Gaussian input pulses, each with a FWHM time width of ~3.3 ps (corresponding rising time ~2.5 ps), generated from a wavelength-tunable mode-locked fiber laser (MLFL), repeating at 17.6MHz, centered at the corresponding grating wavelength. The experimentally characterized reflected ultrashort temporal pulse responses of the FBG-based first- and second-order integrators are plotted in Figs. 2(a) and 2(b) (blue solid lines), respectively. For comparison the temporal impulse responses (numerically shifted from origin for comparison) of the ideal corresponding devices are also plotted with red dashed lines. The characterized ultrashort temporal pulse responses for first- and second-order FBG-based integrators respectively exhibited the desired uniform and linear time profiles over the prescribed finite operation time window of duration $T_h \approx 60$ ps.

The energetic efficiencies (ratio between the output and the input average powers) of the reported ultrashort temporal pulse response experiments for the FBG-based first- and second-order integrators were measured to be 2.88% and 2.89%, respectively. For completeness, we have conducted a similar ultrashort temporal pulse response experiment on our previously demonstrated weak-coupling FBG first-order integrator [5] (using the same input pulses), which was designed to operate over a shorter time window (~50-ps); the measured energetic efficiency in this case was only 0.21%. It is important to note that an improved energetic efficiency is expected for a passive integrator having a shorter operation time

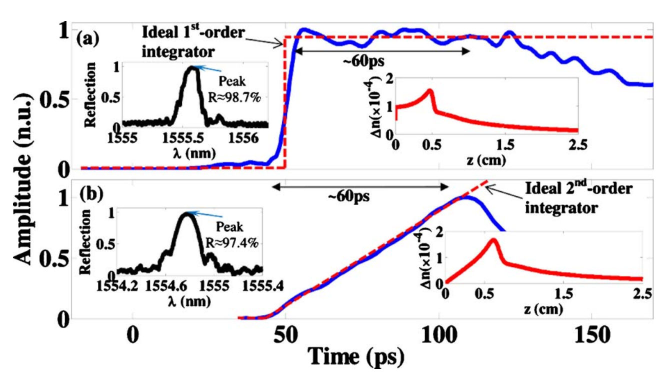

Fig. 2. (Color online) Experimentally measured ultrashort temporal pulse responses of the fabricated FBG-based (a) first- and (b) second-order temporal integrators (blue solid lines) compared to the corresponding ideal temporal impulse responses (red dashed lines). The insets in each plot show the designed FBG apodization profile and the corresponding FBG reflection amplitude spectral response.

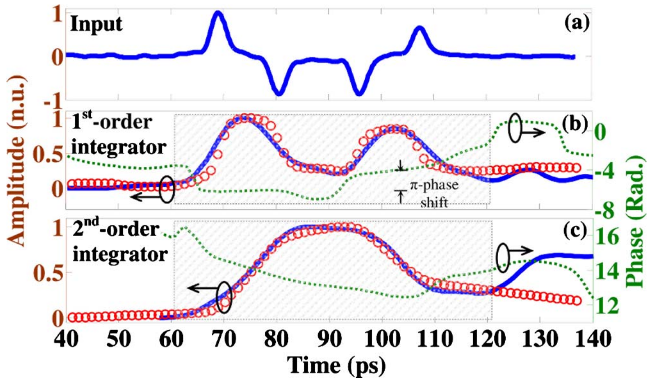

Fig. 3. (Color online) Reflection temporal responses to the input optical signal with the measured temporal envelope plotted in (a). Experimentally recovered amplitude (blue solid line) and phase (green dotted line) temporal profiles of the reflected optical waveform from (b) first-order and (c) second-order temporal integrator, compared to the ideal output amplitude profile, i.e., numerical first-order and second-order cumulative time integration of the signal in (a) (red circles). The operation time window in each case is indicated with a gray hatched box.

window. Thus, in addition to provide a longer operation time window, our newly demonstrated first-order integrator offered more than a 13-fold improvement in terms of energetic efficiency as compared with the previously demonstrated FBG first-order integrator design.

To confirm the operation of the fabricated FBG devices as ultrafast photonic integrators, we measured the temporal responses of these gratings to various properly shaped input optical waveforms. In the example presented here, the input was prepared using an optical pulse shaper unit based on a two-stage bulk-optics interferometric setup (composed by two concatenated Michelson interferometers, I_1 and I_2, see Fig. 1) generating four consecutive, nearly identical transformed-limited Gaussian-like optical pulses (centered at the corresponding grating wavelength for each case), each with a FWHM time width of ~5 ps and relatively delayed from the first Gaussian-like pulse by ~11.4 ps, ~26.2 ps, and ~37.8 ps. The second and third pulses were π-phase shifted with respect to the first Gaussian pulse whereas the fourth pulse was in-phase with respect to this first Gaussian pulse. The normalized measured temporal envelope of this input optical signal, as retrieved from the FTSI technique, is shown in Fig. 3(a). The normalized complex temporal envelope of the optical waveform measured after reflection from the fabricated first-order FBG-based temporal integrator is plotted in Fig. 3(b) (amplitude and phase profiles are shown with solid blue and dotted green lines, respectively) compared to the numerically calculated first-order cumulative time integral of the input temporal envelope (amplitude profile with red circles, shifted from origin for better comparison). There was a very good agreement between the measured reflected waveform and the corresponding ideal output along the anticipated integration time window of ~60 ps (indicated with a gray hatched box). The experimental results corresponding to the measured temporal optical waveform after reflection from the fabricated FBG-based second-order temporal integrator are plotted in Fig. 3(c). The measured amplitude and phase profiles of the reflected waveform are plotted with solid blue line and dotted green line; the experimentally recovered output profile agrees very well with the numerically calculated second-order cumulative time integral of the input signal in Fig. 3(a) (numerical integral plotted with red circles, shifted from origin for better comparison) along the operation time window of ~60 ps (indicated with a gray hatched box). The output phase profile also followed the expected nearly linear variation (corresponding to a transform-limited pulse).

In summary, we have experimentally demonstrated a recently proposed passive design approach for optimized arbitrary-order temporal integration of ultrafast optical waveforms based on the use of a single especially apodized uniform-period FBG. Both first- and second-order ultrafast photonic integrators have been fabricated and tested, successfully proving their capability for accurately and efficiently processing arbitrary optical waveforms with picosecond time features over an operation time window of ~60 ps. The demonstrated FBG design approach would enable implementing practically feasible and efficient ultrafast photonic integrators of any given order, as desired for a wide range of potential applications in all-optical computing, information processing and control.

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