Single-shot photonic time-intensity integration based on a time-spectrum convolution system

Antonio Malacarne,[1,*] Reza Ashrafi,[1] Ming Li,[1] Sophie LaRochelle,[2] Jianping Yao,[3] and José Azaña[1]

[1]Institut National de la Recherche Scientifique—Énergie, Matériaux et Télécommunications (INRS-EMT), Varennes, Québec J3X 1S2, Canada

[2]Center for Optics, Photonics and Laser (COPL), Université Laval, Québec G1V0A6, Canada

[3]Microwave Photonics Research Laboratory, University of Ottawa, 800 King Edward Avenue, Ontario K1N 6N5, Canada

*Corresponding author: antonio.malacarne@ircphonet.it

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Real-time and single-shot ultra-fast photonic time-intensity integration of arbitrary temporal waveforms is proposed and demonstrated. The intensity-integration concept is based on a time-spectrum convolution system, where the use of a multi-wavelength laser with a flat envelope, employed as the incoherent broadband source, enables single-shot operation. The experimental implementation is based on optical intensity modulation of the multi-wavelength laser with the input waveform, followed by linear dispersion. In particular, photonic temporal intensity integration with a processing bandwidth of 36.8 GHz over an integration time window of 1.24 ns is verified by experimentally measuring the integration of an ultra-short microwave pulse and an arbitrary microwave waveform. © 2012 Optical Society of America

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Analog temporal integration is a basic operation for a very wide range of applications in computing, information processing, and communication systems [1]. Analog temporal integration, performed in the optical domain, offers a far superior processing speed than its electronic domain counterpart. In particular, advanced microwave device designs are needed to achieve temporal integrators with operation bandwidths in the GHz range [2]. However, in most cases, these advanced designs suffer from very limited integration time windows, leading to an unpractical performance, e.g., as evaluated in terms of the device time-bandwidth product (typically <5). Within the optical domain, some recent experimental demonstrations of photonic integrators [3–5] have targeted integration of the temporal complex envelope of the incoming signals. Nonetheless, the experimental work presented here is about temporal integration of optical intensity signals (e.g., broadband microwave signals), which can be considered as the direct optical counterpart of a conventional electronic integrator [2]. While photonic intensity integrators have been previously proposed [6] and demonstrated [7,8], significantly overcoming the above-mentioned performance limitations of present electronic solutions, all previous photonic schemes operate on the average of the output signals. In other words, these schemes are fundamentally limited to operation on repetitive input waveforms. Conversely, in this work we demonstrate a photonic intensity integrator operating in single-shot while offering a performance similar (if not superior) to that of previous photonics solutions [7,8].

Photonic intensity integration has been experimentally demonstrated using an incoherent optical filtering setup [7,8]. This approach can offer a processing bandwidth in the tens of GHz range over nanosecond integration time windows, well beyond the capabilities of present electronic/microwave techniques. The method is based on the superposition of mutually "incoherent" (phase-uncorrelated) continuously time-delayed replicas of the optical intensity waveform under test [7]. The actual implementation exploits the time-spectrum convolution concept [9]. This method employs optical intensity modulation of a rectangular-shaped continuous incoherent energy spectrum distribution with the time-domain waveform to be processed, followed by propagation through a dispersive medium consisting of a spool of fiber with predominant linear group-velocity dispersion (GVD). In particular, through the intensity modulation of an optical incoherent broadband source, the intensity waveform to be processed (e.g., microwave voltage signal) is "copied" into an infinite set of incoherently related identical replicas, each one centered at a different wavelength. The continuous set of wavelength-shifted replicas of the input waveform will be time-delayed with respect to each other as a result of the applied GVD. Such time-delayed copies of the original temporal waveform will actually add up in intensity, as expected for an incoherent interference process. Because of the "incoherent" time beating among the different optical signal replicas [10,11], the intensity integration will be obtained in the *averaged* output signal only. The need to average multiple realizations of the output signal to carry out the desired intensity integration represents a fundamental limitation for the practical use of this method, e.g., it cannot be applied to real-time processing of arbitrary (non-repetitive) signals.

Here, we propose and experimentally prove a fiber-optics method enabling real-time and single-shot intensity integration of microwave signals with bandwidths in the tens of GHz range over nanosecond integration time windows. Instead of a continuous incoherent energy spectrum distribution, our method employs a "discrete" version of it, i.e., a periodic frequency comb spectrum ideally having a rectangular-shaped envelope, see schematic in Fig. 1(a). By making use of a discrete comb spectrum with a free-spectral-range (FSR) larger than the bandwidth of the output photodiode (PD), the incoherent beating between the different optical signal replicas will occur at frequencies outside the passband of the PD,

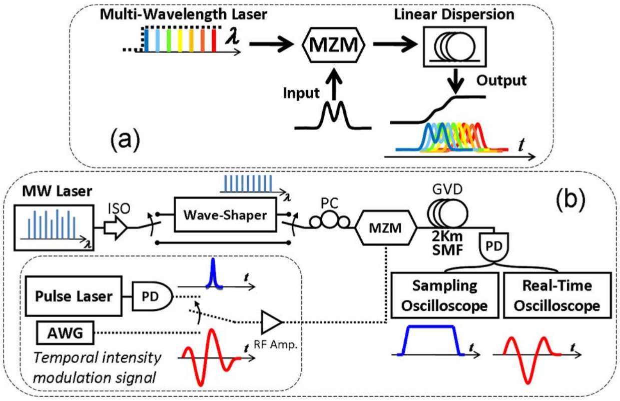

Fig. 1. (Color online) (a) Schematic diagram of the photonic intensity integration process. (b) Experimental setup for the proof-of-concept demonstration of the proposed method.

i.e., the beating will be intrinsically filtered out by the PD. This way the integration operation can be achieved in a single-shot basis, with no need for any average on the output signal. This same idea has been successfully used for signal-to-noise ratio improvement in the context of microwave photonic filters [10] and photonic-based arbitrary waveform generation [11].

Concerning the system design, in order to ensure that the amount of optical GVD $|\ddot{\Phi}|$ ($\ddot{\Phi} = \partial^2\Phi/\partial\omega^2$, where Φ is the spectral phase transfer function of the medium and ω is the optical angular frequency variable) does not cause a distortion on the input intensity waveform. Thus, the GVD must be roughly smaller than the square of the fastest time feature of the input waveform dt^2 [7]. In addition, dt must be significantly longer than the sampling time of the system's temporal impulse response, i.e., $dt > |\ddot{\Phi}|\delta\omega$, where $\delta\omega$ is the radial frequency spacing (FSR) of the multi-wavelength comb laser. This latter condition determines the maximum processing bandwidth ($\sim 1/dt$) of the proposed integrator. Additionally, the integration time window (T) is determined by the dispersion-bandwidth product (DBP) in the system, i.e., $T \sim |\ddot{\Phi}|\Delta\omega$, where $\Delta\omega$ is the total bandwidth of the multi-wavelength laser [7]. Thus, the time-bandwidth product of the integrator, T/dt, is roughly given by the ratio between the laser bandwidth and its FSR, i.e., by the number of spectral lines of the frequency comb laser.

Figure 1(b) shows a scheme of the experimental setup. A multi-wavelength fiber laser with an FSR of $\delta\omega = 2\pi \times 100$ GHz and a bandwidth of about $\Delta\omega \sim 2\pi \times 4.65$ THz, centered at a wavelength of 1544 nm, is employed as the incoherent input optical discrete spectrum. A full description of this all-fiber frequency comb laser system can be found in [12]. In order to properly shape the input comb spectrum profile to achieve a flat envelope, we make use of an electronically programmable optical filter [WaveShaper (WS) 4000 S, Finisar] with a 10 GHz wavelength resolution and an operation bandwidth of ~5 THz. We recall that a uniform energy spectrum is needed to ensure that the waveform at the PD output reproduces, as closely as possible, the input signal integral without requiring any additional numerical post-processing. The latter would affect the system processing speed if the integral is to be used for further computations in a more complex system. Following the spectral shaping module (WS), the required intensity modulation is implemented by a conventional 40 GHz Mach–Zehnder modulator (MZM), followed by a 2 km long spool of SMF ($|\ddot{\Phi}| \sim 43$ ps^2) as the dispersive medium. The bandwidth of the output PD, of 40 GHz, is small enough to cut off any contribution of the incoherent temporal beating present on the output optical signal at frequency components higher than 100 GHz, i.e., the laser FSR. The output signal is finally monitored with both a fast sampling oscilloscope (CSA8000, Tektronix Inc.) for measuring the fastest temporal response of the output waveform, and an 8 GHz real-time oscilloscope (DPO70804, Tektronix Inc.) for full demonstration of the single-shot operation.

In the first experiment, we target the measurement of the temporal impulse response of the system by use of a short pulse as the temporal intensity modulation signal. The electrical pulse is obtained from photodetection of a picosecond optical pulse generated from a passively mode-locked fiber laser (repetition rate ~5 MHz). As mentioned, the employed PD has a 40 GHz bandwidth followed by a 50 GHz RF driver amplifier. Figure 3(c) shows the impulse response in sampling mode (no average). This measurement proves that our integrator is not restricted to work on an average-intensity basis, as in previous implementations [7,8]. However, it should be mentioned that the measured trace presents a low SNR because of the WS insertion loss (~5 dB), leading to an output signal power comparable to the sensitivity of the time domain measurement equipment. Figure 2(b) shows the same trace averaged 50 times (red) compared with the ideal pulse integration (green) and a simulation result (black) carried out considering the measured input pulse (blue), the comb spectrum after equalization [Fig. 2(a)], and a GVD of 43 ps^2. The same measurement and data analysis have been repeated bypassing the spectrum equalization, leading to a better SNR. The measured comb spectrum is shown in Fig. 2(c) whereas the corresponding temporal traces are shown in Fig. 2(d). In this case, the presented measurements are taken in sampling mode with no averaging; see also Fig. 3(b). As expected, the temporal impulse response also exhibits higher fluctuations, as clearly seen from comparison of Figs. 2(b) and 2(d). This is due to the fact that the amplitude fluctuations of the input comb spectrum along the wavelength domain [Figs. 2(a) and 2(c), respectively] are mapped into the corresponding temporal impulse response. Finally, to demonstrate the single-shot operation, the same signal shown in Fig. 2(d) was captured with the 8 GHz real-time oscilloscope with measurement shown in Fig. 3(a).

From the measured temporal impulse response trace (red curve in Fig. 2(e)), a rise time of 27.2 ps (corresponding to a ~36.8 GHz operation bandwidth) and an integration time window of 1.24 ns were respectively measured. These measured values are in excellent agreement with the predicted ones, i.e., $dt > |\ddot{\Phi}|\delta\omega \sim 27$ ps and $T \sim |\ddot{\Phi}|\Delta\omega \sim 1.25$ ns.

Finally, to attest the correct operation over the entire integration time window, an arbitrary microwave signal with frequency content up to 2 GHz was produced by an arbitrary waveform generator and used as the temporal

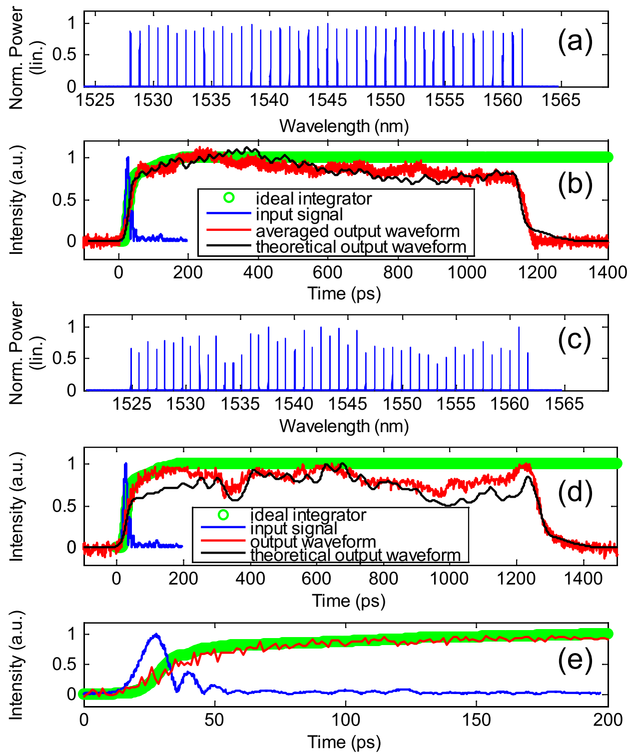

Fig. 2. (Color online) Comb laser spectrum after equalization (a) and corresponding experimentally measured temporal impulse response, averaged 50 times. (b) Input comb laser spectrum (c) and corresponding experimentally measured temporal impulse response (without equalization), in sampling mode (no averaging). (d) Zoom of figure (d) except the black curve (e).

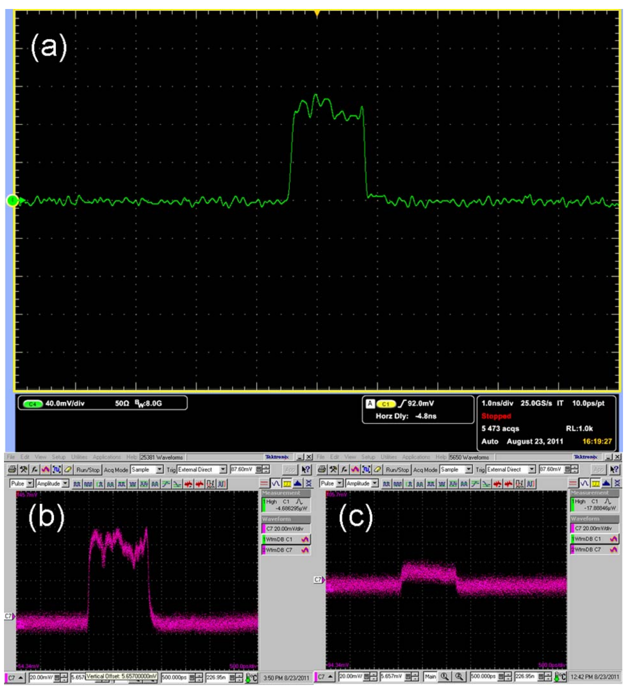

Fig. 3. (Color online) (a) Real-time oscilloscope trace of the impulse response without equalization and with no averaging (i.e., single-shot). Sampling oscilloscope traces (with no average) of the impulse response without equalization (b) and with equalization (c).

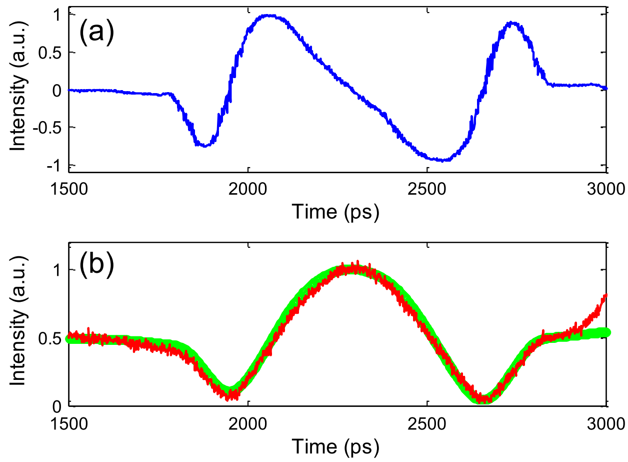

Fig. 4. (Color online) Measured (no averaging) photonic intensity integration in sampling mode (b) of an input arbitrary microwave signal (a) with equalization filtering.

intensity modulation signal (input signal to be processed). Figure 4 shows the measured input [blue curve, Fig. 4(a)] and output [red curve, Fig. 4(b)] waveforms grabbed in sampling mode (no averaging), in very good agreement with the ideal integration of the input signal (green curve, Fig. 4(b)) over a time range of about 1.3 ns. The incoherent spectrum for this latter case was the same as that reported in Fig. 2(a).

To conclude, we have proposed and experimentally proved a fiber-optics scheme for real-time and single-shot temporal intensity integration of optical and microwave signals, simultaneously offering a high processing bandwidth of 36.8 GHz and a long operation time window of 1.24 ns, i.e., well beyond the reach of present electronic/microwave methods. The system overcomes the main limitation of previous photonic implementations, i.e., “in-average” operation, enabling the processing of non-repetitive waveforms. Single-shot operation has been achieved using a multi-wavelength fiber laser with a flat-shaped envelope. The method should prove particularly useful for customized generation and processing of broadband microwave signals.

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