Time-gated filter for sideband suppression

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A time-gated filter is demonstrated that converts a double-sideband radio-frequency (rf) waveform on a pulsed optically chirped carrier into a single sideband (SSB) waveform. Electrical technology to produce SSB modulation is currently limited to rfs less than 20 GHz, while our filter operates up to the maximum frequency available from optical modulators. Application of the filter in photonic time-stretch analog-to-digital converters (TS-ADCs) mitigates severe frequency fading owing to the dispersion penalty that limits the rf input signal bandwidth and time aperture. Here we show that frequency fading owing to the presence of both upper and lower sidebands in the TS-ADC can be reduced by over 20 dB and that a TS-ADC using this filter can digitize electrical signals with rfs beyond 100 GHz.

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Conventional techniques used to modulate radio-frequency (rf) signals on an optical carrier produce an optical signal that consists of the carrier itself plus upper and lower sidebands at the optical frequency plus and minus the rf. In microwave photonic links with chromatic dispersion the three signals travel at different velocities. At the end of the link where the upper and lower sidebands beat with the carrier on a photodetector, the rf signal recovered from the upper sideband is out of phase with the rf recovered from the lower sideband. The consequences of this "dispersion penalty" can be severe enough that it is desirable to suppress one of the sidebands, and often a conventional optical filter can do this. Alternatively, single sideband (SSB) signals may be obtained directly from a dual-electrode electro-optic modulator driven by the in-phase and quadrature components of an rf signal [1]. This technique is straightforward for narrowband rf signals but requires additional electronics for broadband signals, and these electronics are currently limited to frequencies below about 20 GHz [2]. For a system, such as the time-stretch photonic analog-to-digital converter (TS-ADC) [3], the optical carrier is rapidly chirped over 10 nm or more, and conventional optical filters are not useful. Also in this system, there is interest in broadband rf signals with bandwidths of 100 GHz or more, so the dual-drive approach is not feasible. Here we demonstrate a time-gated filter (TGF) that achieves sideband suppression for rapidly chirped optical pulses and rf signals up to the bandwidth limit of existing modulator technology. While the TGF is developed for our application, the TS-ADC, it may have other applications when an rf signal is modulated on a chirped optical carrier and this combined signal propagates through a dispersive medium.

As shown in Fig. 1, the TGF contains three elements: a chirp tranform, a time gate, and an inverse chirp transform. An rf signal at f_m is modulated on an optical carrier chirped by total dispersion d ps/nm ($d=DL$ for a fiber, where D is the conventional dispersion parameter and L is the length of the fiber) about a center carrier frequency f_c, and this produces sidebands at $f_c \pm f_m$. The optical signal is then recompressed using complementary total dispersion $-d$ to produce an optical signal that consists of a center pulse and two symmetrically spaced satellite pulses in the time domain corresponding to the carrier and the upper and lower sidebands [4,5]. The complementary dispersion should be equal in magnitude and opposite in sign to that on the incident optical signal for optimal compression. The time shift between the sidebands and the center pulse is given by $t_m = f_m|d|\lambda^2/c$ [4, Eq. (4)]. Next, a time gate removes one of the satellite pulses and effectively filters out one of the sidebands using the pulse shaping process. Finally, an inverse chirp transform is obtained by propagating through a medium with dispersion $+d$ to obtain a SSB chirped optical signal.

Figure 2 shows the experimental setup for the TGF integrated within a time stretch analog-to-digital converter (ADC). A 20 MHz femtosecond-pulsed laser with 30 nm bandwidth centered at 1550 nm is used both in the TS-ADC (the optical path from the upper output of the WDM that enters the circulator) and in a simple version of a photonic arbitrary waveform generator (the optical path from the lower output of the WDM that enters the fiber with $d=-331$ ps/nm)

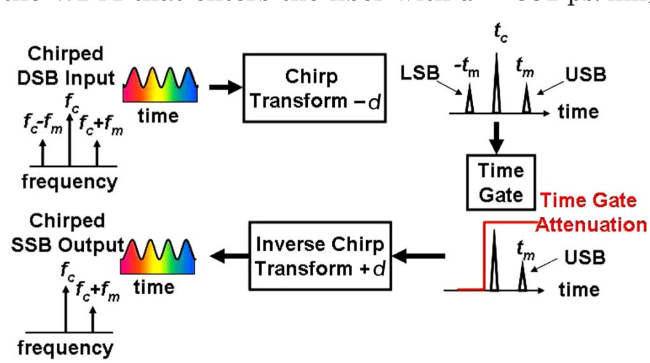

Fig. 1. (Color online) Schematic of the dispersive Fourier transform filter (DSB, LSB, USB, and SSB, double, lower, upper, and single sideband, respectively). The DSB waveform input at the upper left is converted by the chirp transform, time gate, and inverse chirp operations to the SSB waveform output on the lower left.

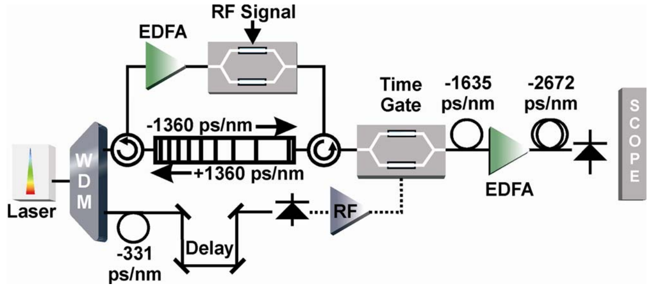

Fig. 2. (Color online) Experimental setup for the TGF integrated within a time-stretch ADC system (WDM, wavelength demultiplexer; EDFA, erbium-doped fiber amplifier; rf, radio frequency). The simple photonic arbitrary waveform generator that drives the time-gate MZM is shown by the lower link in which a 1 nm bandwidth optical pulses propagate from the WDM through the −331 ps/nm fiber and the variable delay stage to the photodiode where they are converted to current pulses that enter the rf amplifier to obtain the voltage pulses that drive the MZM.

that produces the rf waveform that drives the time gate [6]. The optical bandwidth of this lower path is 1 nm, so the pulse duration after the −331 ps/nm fiber is 331 ps. This pulse is converted to a voltage pulse to drive the time gate by the rf electronics following the photodiode. The delay stage is used to precisely synchronize the voltage pulse with the pulse corresponding to the sideband to be attenuated. Using part of the same pulse to drive the time gate means that no further work is required to synchronize the time gate with the double sideband (DSB) signal. The upper output of the WDM is dispersed in the chirped fiber Bragg grating (CFBG) with $d=-1360$ ps/nm, exits the circulator, is amplified and

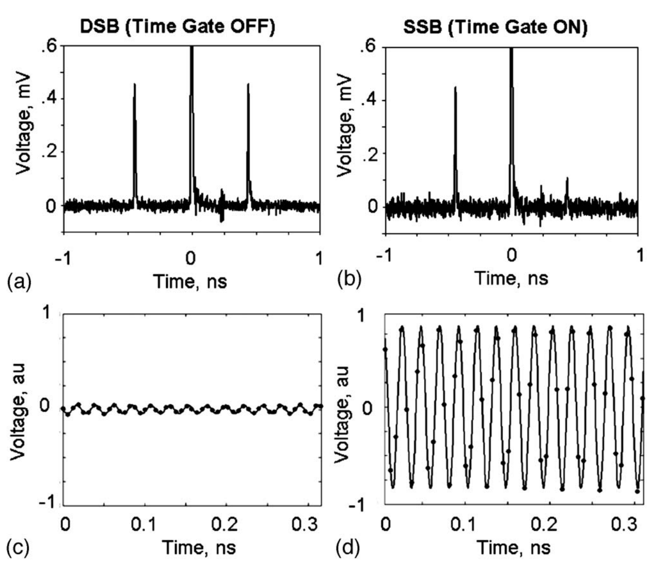

Fig. 3. Single-shot data for the time stretch ADC with both sidebands present (DSB, time gate off) and single sideband (SSB, time gate on). (a) Time domain signal with time gate off. (b) Time domain signal with time gate on showing attenuation of one pulse corresponding to upper sideband. (c) Recovered rf signal as a function of time with time gate off, showing highly attenuated signal because of the presence of both sidebands and the dispersion penalty. (d) Recovered rf signal with time gate (SSB) on showing increased signal in the absence of the dispersion penalty.

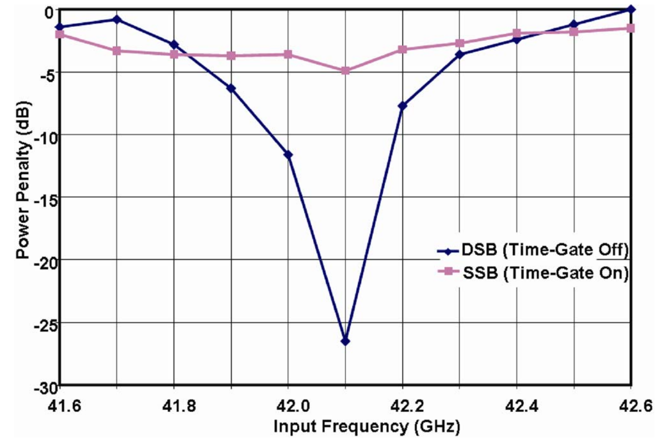

Fig. 4. (Color online) Power penalty (dispersion penalty) as a function of input frequency with the time gate off (DSB, both sidebands present) and the time gate on (SSB).

modulated by the rf signal in the upper Mach–Zehnder modulator (MZM). Then it is compressed by chirp transform with $d=1360$ ps/nm by using the CFBG in the opposite direction (from the right) and sent through the time-gate MZM. Following this MZM are the conventional components in the second half of a TS-ADC: a dispersive fiber ($d=-1635$ ps/nm), an erbium-doped fiber amplifier (EDFA), a second dispersive fiber ($d=-2672$ ps/nm), a photodiode, and a back-end ADC. Note that if the dispersive fiber with $d=-1635$ ps/nm is split into two fibers such that the length of the first fiber gives dispersion $d_1=-1360$ ps/nm and that of the second gives $d_2=-275$ ps/nm, one may obtain the SSB signal itself directly after the first fiber, which performs the inverse chirp transform. The stretch ratio 3.17 is given by the sum of the fiber dispersions divided by the CFBG dispersion. If the time gate is off, the dispersion penalty results in 19 transmission nulls between 0 and 50 GHz.

Figure 3 shows the performance of the TS-ADC for a 40 GHz tone located near one of the transmission nulls caused by the dispersion penalty. The time-domain optical waveforms before and after the time gate are captured using a 75 GS/s optical sampling oscilloscope. Figures 3(a) and 3(b) show the waveforms when the gate is turned off and on, respectively, while Figs. 3(c) and 3(d) show the corresponding rf signals as digitized at the output of the time-stretch ADC. When the filter is off, both sidebands propagate through the system and interfere with the carrier at the photodiode. As predicted, the signal experiences high attenuation owing to fading near a frequency null. When the filter is turned on, the upper sideband is suppressed, and the signal power increases by approximately 22 dB.

There are three interrelated limitations on the frequency response of the time-gated filter. First, if the radio frequency f_m is too small, the sidelobes in the time domain will be too close to the center lobe for the MZM switch to remove them. Second, if the response time of the TGF MZM is too slow, the switch will not be able to cleanly eliminate the upper or lower sideband in the time domain. Finally, the voltage pulse

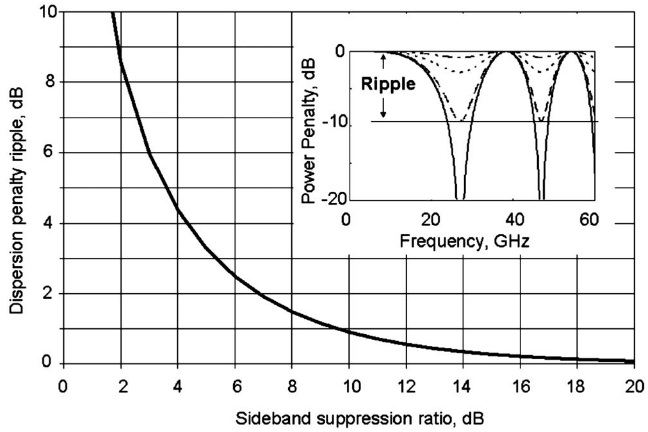

Fig. 5. Calculated dispersion penalty ripple as a function of sideband suppression ratio. The inset shows the dispersion penalty for sidelobe suppression ratios 2, 5, and 10 dB (large-dashed, small-dashed, and dotted–dashed curves, respectively.

used to switch the TGF must turn on and off sufficiently fast in time. These limitations have been discussed in detail previously [4,5]. In an application such as the TS-ADC, one is generally interested in an rf above 1 GHz, and the limitations are not severe.

Figure 4 illustrates a swept measurement across a 42.1 GHz null for a SSB and DSB signal. As the signal is detuned away from the null, a ~3 dB power difference is expected between the SSB and DSB format. Figure 5 shows a theoretical calculation of the dispersion penalty ripple as a function of sideband suppression. The sidelobe suppression obtained from the measurements shown in Figs. 3(a) and 3(b) is about 7 dB, and this translates using the calculation shown in Fig. 5 to a ripple of less than 2 that is consistent with the remaining ripple in the curve labeled SSB in Fig. 4.

In summary, we have demonstrated a method to remove one sideband of a pulsed optical signal that is rapidly chirped. We have used this method to nearly eliminate the dispersion penalty in a time-stretch photonic ADC operating at 150 GS/s.

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