Temporal cloaking for data suppression and retrieval: supplementary material

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This document provides supplementary information for “Temporal cloaking for data suppression and retrieval,” <http://dx.doi.org/10.1364/optica.1.000372>. In it we discuss details of the design conditions for the multi-wavelength cloak, provide a summary of the experimental procedures, and identify directions for future development. © 2014 Optical Society of America

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1. DESIGN OF MULTI-WAVELENGTH CLOAK

Temporal synchronization of both input wavelengths is achieved by precisely matching group delay through all dispersive elements. In general, a lossless second-order dispersive medium multiplies the incident frequency spectrum by the complex filter $H(\omega) = \exp[j\psi_2(\omega - \omega_0)^2/2]$, where ω represents the angular frequency, j the imaginary unit, ψ_2 the medium's dispersion coefficient, and ω_0 the center frequency of the expansion; in this form we have neglected an unimportant constant delay. The frequency-dependent group delay follows on evaluating the derivative of the filter phase: $\tau(\omega) = -\frac{d}{d\omega} \arg H(\omega)$. Therefore, two carrier frequencies ω_1 and ω_2 will temporally separate on propagation through the medium by an amount $\Delta\tau = \tau(\omega_1) - \tau(\omega_2) = -\psi_2\Delta\omega$, where $\Delta\omega = \omega_1 - \omega_2$.

In order that both wavelengths precisely overlap in time at the second phase modulator in our cloak—necessary to generate flat frequency combs that will compress to clean pulses—we require delay matching at a multiple of the temporal period, i.e.

$$|\Delta\tau_{\text{CFBG}}| = \frac{2\pi p}{\omega_{\text{rep}}}, \quad (\text{S1})$$

where p is a nonnegative integer and ω_{rep} signifies the angular frequency of the electro-optic modulation (CFBG is short for “chirped fiber Bragg grating”). Even though we slightly detune the clock frequency from the Talbot condition in experiment, for conceptual simplicity here, we consider the CFBGs to apply quarter-Talbot dispersion, $|\psi_2| = \pi/\omega_{\text{rep}}^2$, which combined with the previous constraint fixes the possible frequency separations at

$$|\Delta\omega| = 2p\omega_{\text{rep}}. \quad (\text{S2})$$

Thus any two lasers whose frequencies differ by an even multiple of the clock frequency will satisfy the first timing condition. Yet we also require that the waveforms at each wavelength be interleaved at the event, so the relative delay through the optical fiber link must satisfy

$$|\Delta\tau_{\text{fiber}}| = \frac{2\pi}{\omega_{\text{rep}}} \left(q + \frac{1}{2} \right) \quad (\text{S3})$$

with q another nonnegative integer. Defining R as the ratio between CFBG and fiber dispersion coefficients $R = |\psi_2^{(\text{CFBG})}|/|\psi_2^{(\text{fiber})}|$, and recalling the first timing condition [Eq. (S2)], one finds that both are met if p and q can be found such that

$$p = R \left(q + \frac{1}{2} \right). \quad (\text{S4})$$

Exact solutions exist only if the dispersion ratio R is an even integer; in our case, the fiber dispersion links were chosen previously for temporal compression, and so we are left with $R = 23.7$. We thus focus on the case $p = 12$, $q = 0$, which exactly meets the CFBG timing condition but only approximately the interleaving requirement. Yet this deviation is minor; the interleaved pulse trains are now shifted by ~51% of the temporal period instead of 50%, and since the second train need only avoid the event modulation—precise matching of phase is unnecessary—overall performance remains strong. Experimentally, our procedure is to first find a frequency spacing that gives approximately 50% interleaving and then fine-tune the separation to ensure temporal matching through the fiber Bragg gratings.

2. DETAILS OF EXPERIMENT

As light sources, we utilize two commercial continuous-wave lasers, one at a wavelength of around 1541.4 nm (NP Photonics “The Rock”) and the other tunable (Agilent 81689A). A low-noise radio-frequency oscillator (Agilent E8257D) supplies the 12.11-GHz clock signal which drives all four EOSpace phase modulators and synchronizes the measurement equipment. The chirped fiber Bragg gratings (Proximion DCM-PC) have nominal dispersions of ± 400 ps/nm, and the interior fiber links have approximately ± 17 ps/nm; the final output fiber applies a dispersion of roughly 400 ps/nm.

The length $2^{31} - 1$ pseudorandom data sequence acting as the event is generated by a bit-error-rate tester (Agilent N4901B) and electronically converted to a return-to-zero format before it is applied to a high-speed intensity modulator (Photline MX-LN-40). An arbitrary waveform generator (Tektronix AWG7122B) creates the data stream used as input in the second set of cloak tests, which is modulated onto the input laser with a 10-GHz intensity modulator from EOSpace; here the sequence is $2^{15} - 1$ bits long. Two erbium-doped fiber amplifiers from PriTel compensate for system loss, one at the input and the other at the output, and final frequency-domain measurements are made on an optical spectrum analyzer with 0.01-nm resolution (Ando AQ6137B). In the multi-wavelength cloak, a commercial pulse shaper (Finisar WaveShaper 4000S/X) is used to separate output channels. Photodetectors with 12.3-GHz bandwidth (Agere 2560A-C02) convert the received optical intensities to electrical signals which are subsequently measured on a sampling oscilloscope (Tektronix DSA8200).

3. POSSIBILITIES FOR FUTURE IMPROVEMENT

There remain several avenues for improvement on these new cloaking capacities, several of which were identified in [1]. For example, drift in the optical delay between modulators, caused by the thermo-optic effect, requires us to readjust the phase of the microwave drive signals every few minutes to maintain optimum cloaking. Replacing these long fiber links [SMF and DCF in Fig. 1(b)] with chirped fiber Bragg gratings would circumvent this issue, permitting stability over several hours under our laboratory conditions. Additionally, it would be beneficial to consider cascading multiple phase modulators at points II and V in Fig. 1(b), which would significantly broaden the bandwidth of the generated frequency combs and support much shorter probe pulses at the event modulator [2], thereby further reducing the event’s impact on the probe and minimizing residual modulation at the cloak output.

In addition to the aforementioned improvements, one could pursue an arrangement composed entirely of polarization-

maintaining components. Currently, polarization controllers are required before every modulator, increasing both system loss and susceptibility to environmental fluctuations. Even better would be to implement the cloak with on-chip modulators, which would allow for precise engineering of the waveguides and dispersion. Indeed, we believe the stronger parasitic modulation in the two-wavelength case (Fig. 2) results from a slight dispersion mismatch, preventing the pulse trains at both wavelengths from maintaining timing synchronization at all modulators. Thus improved dispersion control would offer strong performance gains in the multi-wavelength case in particular.

More generally, we see two major avenues for progress on the multi-wavelength cloak’s functionality. First, instead of considering only two wavelengths, it is feasible to directly extend our technique to several evenly spaced frequencies, in which cloaked and data-transmitting channels alternate along the grid. The total number of potential channels would be limited only by the acceptance bandwidth of the optical components. Second, programmable delay control would permit multi-wavelength cloaking with arbitrary laser channel frequencies, instead of the precisely chosen values in this experiment. This could in principle be implemented by placing pulse shapers [3, 4] before and after each of the inner phase modulators in Fig. 1(b) (e.g., at locations II, III, IV, and V). By applying spectral phase shifts corresponding to the desired group delays, it would then be possible to control which wavelength channels are cloaked and which pick up data, with complete programmability and no restriction to particular frequency spacings. Implementation of this scheme would demand relatively fine spectral resolution, roughly on the order of the cloak repetition frequency, in order to permit the half-period shifts necessary to move a channel’s delay from cloaked to uncloaked positions. Nevertheless, systems like the current one designed only for particular wavelength separations could find use even without the added capabilities furnished by multiple pulse shapers, as certain optical communication techniques such as orthogonal frequency-division multiplexing already require precisely spaced channels at multiples of the symbol rate.

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