Continuous coherent transient optical processing in a solid

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We report what is to our knowledge the first experimental demonstration of a continuous coherent transient optical processor. A 13-bit pattern was stored as a spectral population grating in the Eu^{3+}-ion ground state in a Eu^{3+}:Y_2SiO_5 crystal. A 3120-bit data stream was processed continuously, yielding a cross-correlation signal that agreed well with theory. The data stream's duration exceeded both the absorbing transition's homogenous transverse dephasing time and upper-state lifetime. This experiment showed that by permanently storing the pattern as a population grating in the absorber's ground state, coherent transient optical devices provide continuous, real-time data processing capability. © 1995 Optical Society of America

When a sequence of temporally modulated optical waveforms illuminates an inhomogeneously broadened absorbing medium under appropriate conditions, the resultant optical coherent transient signal represents the cross correlation or convolution of the input temporal waveforms.[1] A signal processor for performing cross-correlation or convolution operations realized with coherent optical transient techniques is predicted to outperform significantly the ones realized with conventional technologies. Their projected performance characteristics include data rates greater than 10 GHz, time–bandwidth products in excess of 10,000, and the ability to process fully both amplitude- and phase-modulated waveforms.[1,2] A typical input sequence has three optical waveforms: a pattern stream, a brief reference pulse, and a data stream. When the coherent transient processor was first conceived, it was assumed that the pattern stream and the data stream must both be shorter than the absorbing optical transition's homogenous transverse dephasing time, T_2, and must both be reentered into the medium to process longer data streams.[1] It was recently proposed that patterns (still shorter than T_2) could be permanently stored as a ground-state spectral population grating in an inhomogeneously broadened solid and that data streams of indefinite length (significantly longer than both T_2 and the absorber's excited-state lifetime, T_1) could be continuously processed in real time without the need to reenter the pattern stream.[2]

The programming and processing steps for the continuous coherent transient optical processor require an inhomogeneously broadened absorbing medium in which excited absorbers either decay or are gated into a (preferably infinitely) long-lived trap state that is not resonant with wavelengths of the optical data stream. For the operation of correlation to be programmed, the pattern stream and then the brief reference pulse, temporally separated and angled (or counterpropagating) with respect to each other, must illuminate the medium. Provided that these waveforms are within the data bandwidth of the medium (nominally its inhomogeneous bandwidth) and shorter than T_2, the spectral population distributions of the excited and ground states contain an interference term proportional to the product of the Fourier transforms of the two waveforms. After the decay or gating of the upper-state absorbers to the trap state, the interference term is stored in the spectral population distribution of the remaining ground-state absorbers in the medium.

The resultant population grating acts as a spectral filter on the Fourier components of the coherence induced by the subsequent optical data streams, yielding an output signal $E_{\mathrm{signal}}(t)$:

$$E_{\mathrm{signal}}(t) \propto \iint_{\infty} \mathrm{d}\tau_1 \mathrm{d}\tau_2 \times E_{\mathrm{pattern}}(\tau_1) E_{\mathrm{brief}}(\tau_2) E_{\mathrm{data}}(t + \tau_1 - \tau_2), \quad (1)$$

where $E_{\mathrm{pattern}}(t)$, $E_{\mathrm{brief}}(t)$, and $E_{\mathrm{data}}(t)$ are the waveforms of the pattern, brief pulse, and data streams, respectively. The data stream is not limited in length by T_2 or T_1 and may continue to be processed, without interruption, for as long as the ground-state spectral population grating persists. Three phenomena act to reduce the grating amplitude: saturation of the transition by the data stream, decay of the trap state absorbers back to their original ground states, and optical pumping of the ground-state grating to the trap state.[2] One can minimize the saturation effect by sufficiently lowering the input optical intensity of the data stream. The decay of the trap state depends on the material used, but stored data have been shown to last well over a day in some materials.[3] The optical pumping effect is a significant problem in systems in which writing of the grating is done with a single wavelength (not gated). If the gating step[4] is the only path to transfer the excited absorbers to the trap state, then any ground-state absorber subsequently excited by the data stream would decay (in the absence of the gating step) back to its ground state and restore the programmed spectral grating.

In this Letter we report the experimental demonstration of a continuous coherent transient optical correlator with a Eu^{3+}:Y_2SiO_5 crystal, since the ideal material system for a continuous coherent transient optical processor has not yet been developed. In this crystal the population grating can be formed in the ground-state hyperfine levels of europium ions with long lifetimes (>1 h at $T = 4$ K),[5] and the weakly allowed $^7F_0 \leftrightarrow {}^5D_0$ transition in europium ions has a very long T_2.[5,6] The fact that the pattern is stored as a population grating in the ground-state hyperfine levels of the Eu^{3+}:Y_2SiO_5 crystal means that the stored pattern is susceptible to degradation as a result of optical pumping effects during the data processing interval. This lack of a gating step leads to a slow washing out of the population grating during the processing stage and deterioration in the fidelity of the processor's output signal. Another drawback of this crystal is the small hyperfine splittings, which limit the processing bandwidth because of coherent beating effects.[7] The smallest antihole splitting in ^{151}Eu is 5.7 MHz,[5,8] which limits the maximum data rate to roughly 1 Mbit/s. We used Site 1 of the transition $^7F_0 \leftrightarrow {}^5D_0$ at $\lambda = 579.88$ nm in a 5-mm-long Eu^{3+}:Y_2SiO_5 (0.2% at. wt.) crystal sample, which was maintained at $T = 1.9$ K in the Earth's magnetic field, for all measurements reported in this Letter. The crystal sample's peak absorption was 65%. The lifetime T_1 and the transverse dephasing time T_2 of this transition were measured to be 2 ms and 600 μs, respectively, which agreed with the published values for a crystal under similar conditions.[5,6]

We encoded the pattern and the data streams by using optical phase modulation to obtain more pronounced autocorrelation peaks and to reduce deleterious saturation effects.[2] Figure 1 shows the input waveforms used in this experiment, where a 0 corresponded to no optical phase shift and a 1 corresponded to a π optical phase shift. A 1.0-Mbit/s data rate with nonreturn-to-zero phase coding was used for both the pattern and the data streams. The pattern was a 13-bit code (1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 0, 1), lasting 13.0 μs. The brief pulse had a 1.0-μs duration and started 3.0 μs after the end of the pattern waveform. A 6.24-ms delay between the brief pulse and the start of the data stream permitted more than 95% of excited-state populations to decay before the processing stage began. This delay ensured that the stored ground-state (and not the upper-state) population grating dominated the output signal. The data stream duration (3.12 ms) was limited by the maximum record length of the digitizer used but was sufficiently longer than the excited-state lifetime to illustrate the continuous nature of the processing. The data stream was made up of fifteen 16-segment-long sequences. Each 13-bit-long segment either matched the 13-bit code pattern (P) or were noise segments. Two different noise segments were used: the first (N1) was (1, 0, 1, 0, 1, 1, 0, 0, 0, 1, 1, 1, 1) and the second (N2) was (1, 0, 0, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1). The 16-segment-long sequence was made up of a combination of these segments (P, P, N1, N2, P, N1, P, P, N1, N2, N1, P, N1, P, N2, P) and was repeated 15 times to yield the data stream. Thus the entire data stream was $13 \times 16 \times 15 = 3120$ bits long.

Figure 2 shows a schematic of the experimental setup. To maintain the coherent processor's fidelity we used an external optical phase/frequency stabilizer[9] to lock the ring dye laer (Coherent 699) frequency to an additional reference cavity so that the optical phase difference between the carriers of the pattern and data waveforms fluctuated only a small fraction of π during any coherent processing time interval, i.e., 13 μs. A frequency synthesizer, which drove a double-pass acousto-optic modulator (AOM 1) between the laser system and the reference cavity, permitted the laser frequency to be tuned relative to the resonant frequency of the reference cavity. Precise control of both the power and the phase of this pattern/data beam was realized with an acousto-optic modulator (AOM 2). The optical powers of the pattern stream and the data stream were 5.0 mW and 68 μW, respectively. An acousto-optic modulator (AOM 3) controlled the power and duration of the brief pulse. The optical power in the brief pulse (200 mW) was chosen to create a pulse area of approximately $\pi/2$. The pattern/data beam and the brief pulse beam were aligned to overlap in the Eu^{3+}:Y_2SiO_5 crystal sample with a full angle of 4.6 deg, each with a $1/e^2$ intensity waist radius of 1.0 mm. The laser frequency was shifted from the previous value before every measurement. After several measurements an annealing process was used to erase all persistent spectral gratings. These two measures ensured that the output signal was dominated by the population grating generated from the single illumination by the pattern and the brief pulse just before the data stream.

The two acousto-optic modulators (AOM 4 and AOM 5) in the detection system prevented the powerful brief pulse from reaching the photomultiplier tube (PMT). The signal was digitized at 2 megasamples per second and stored in the computer. Figure 3 shows a typical single-shot (not averaged) output

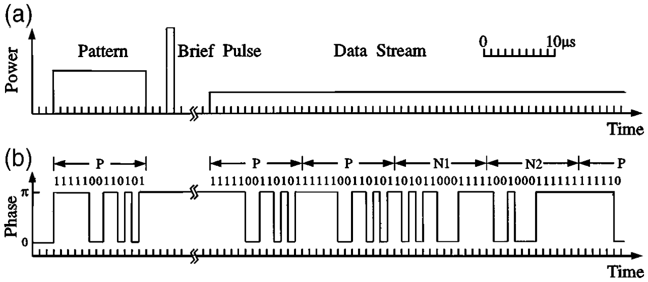

Fig. 1. Input waveforms for the experiment. Only the first four 13-bit segments of the 240-segment-long data stream are fully shown. (a) Powers (not to scale) of the pattern, brief pulse, and data stream. (b) Optical phase of the pattern and data stream. See text for details.

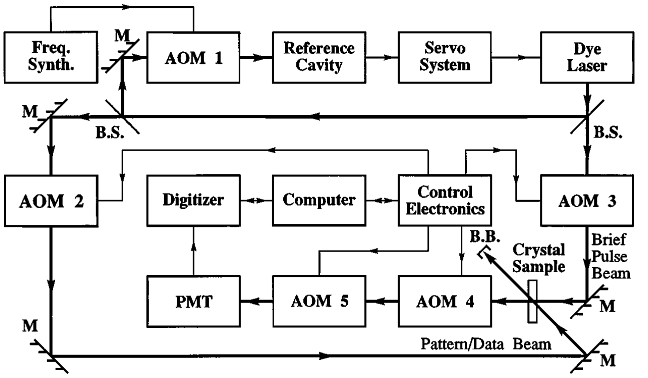

Fig. 2. Schematic of the experimental setup. B.B., beam blocker; B.S.'s, beam splitters; M's, mirrors. The crystal is mounted in a liquid-helium cryostat (not shown).

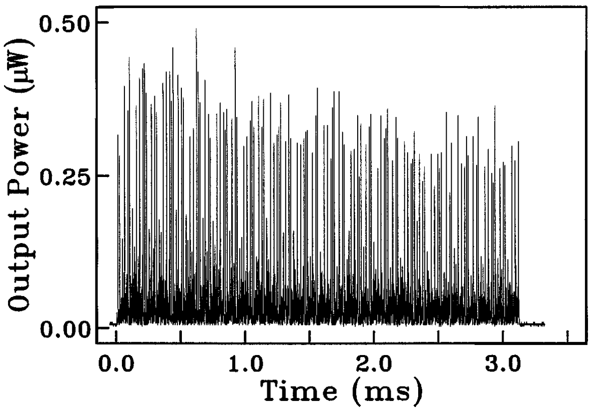

Fig. 3. Detected single-shot (not averaged) output correlation signal. The signal decays only slightly over its duration, approximately 3.12 ms.

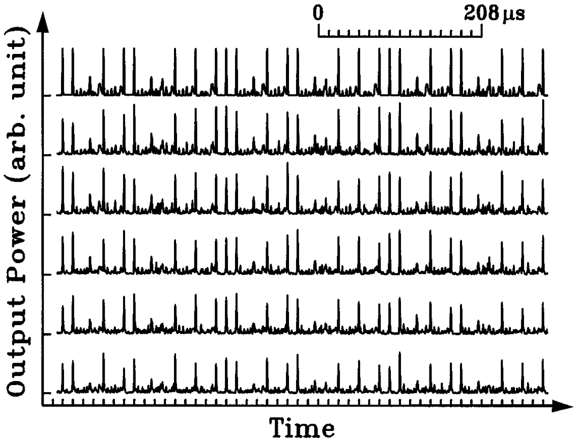

Fig. 4. Same single-shot signal shown in Fig. 3, except that it is broken into five successive 624-μs traces (lower five traces) for comparison with the output signal calculated by relation (1) (the top trace). The vertical scale (signal power) is the same for all five traces of the output signal. The tick marks are separated by 13 μs (the segment length). The calculated signal represents the correlation of the pattern P with a fifth of the data stream.

signal. The peak amplitude of the output signal did not decay significantly during its 3.12-ms duration. This confirmed that the correlator processed the data predominantly based on the ground-state population grating, since the contribution of the residual decaying excited-state population grating to the output signal decreased by a factor of 23 during the 3.12-ms processing interval. The observed slight reduction in the output signal amplitude from beginning to end may come partly from this residual excited-state population grating decay and/or partly from the reduction of the ground-state population grating as a result of the optical pumping of the hyperfine levels by the data stream. Increasing the optical power in the data stream led to a larger decay of the output signal amplitude over its duration, confirming the deleterious effects of optical pumping.

In Fig. 4 we replot the *same* data shown in Fig. 3 in order to compare this experimental result with the calculated correlation obtained by relation (1). The top trace in Fig. 4 is the calculated correlation of the pattern stream and one fifth of the data stream (three repetitions of the 16-segment-long sequences). The repetitive nature of the data stream allows it to be broken up into five 624-μs plots (the five lower plots in Fig. 4) and compared with the calculated data. The output signal matches the calculation very well. The 120 large peaks in the output signal correspond to the 120 appearances of the pattern segment in the data stream. Even the smaller, partial correlations during and between the noise segments were faithfully detected. The fidelity of the output signal did not change significantly within the 3.12-ms output signal duration. The averaged power (emerging from the crystal sample) of the output signal's 120 correlation peaks was 0.3 μW (0.44% of the data stream intensity).

In summary, we have demonstrated what is to our knowledge the first continuous coherent transient optical processor.[10] The pattern and data streams were represented by phase-modulated optical waveforms. The 3120-bit (3.12-ms) data were processed by the stored ground-state spectral population grating. The data processing produced high-fidelity results for a time interval significantly longer than both the transverse dephasing time T_2 and the lifetime T_1 of the transition used. This is to our knowledge the first demonstration of a novel technique for continuous, real-time processing of data with potential ultrahigh bandwidth and ultrahigh time–bandwidth products in appropriate materials.[2]

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