

Accumulated programming of a complex spectral grating

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A complex spectral grating is accumulated by repeated application of a pair of low-power optical programming pulses to a short-term persistent inhomogeneously broadened transition in Tm:YAG at 4.5 K and then probed to investigate the buildup dynamics. The necessary frequency stability is obtained by locking a cw Ti:sapphire laser to a regenerating transient spectral hole in the same transition. Grating accumulation is demonstrated for both a periodic spectral grating, representing a true-time delay, and a complex spectral grating, permitting correlation-based pattern recognition. This work is a step toward demonstrating an optical coherent transient continuously programmed continuous processor. © 2000 Optical Society of America
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The repeated application of optical programming pulses has been used to accumulate and refresh complex spectral gratings on an inhomogeneously broadened transition (IBT) that exhibits long-term persistent spectral hole burning.^{1,2} Recently it was proposed that such techniques could be used in an IBT that exhibits short-term persistence and that the programming and probe pulses could occur simultaneously under certain conditions, allowing for continuous processing operations of probe signals.³ In this instance, accumulation to and maintenance in steady state can be accomplished by the application of relatively low-power, frequency-stable optical pulses, where the excitation by each pulse pair exactly compensates for the decay that occurs between different pulse pairs.⁴ Continuous programming of the spectral grating makes feasible the use of currently available IBT's with short-term persistence in optical coherent transient processing devices such as optical signal cross correlators⁵ and optical true-time delay regenerators.⁶ Provided that the transition is not saturated, the grating can perform continuous spectral filtering of a real-time optical waveform that is modulated in amplitude and phase at data rates greater than 10 GHz and with time-bandwidth products greater than 1000. An additional advantage of continuous programming in IBT with short-term persistence is that the spectral grating can respond and adapt to changes in the programming pulses on the time scale of the persistence. In this Letter we experimentally demonstrate accumulation of a complex spectral grating to nearly steady state on an IBT with short-term persistence, using low-power programming pulses. We obtained the necessary frequency stability by locking a cw Ti:sapphire laser to a regenerating transient spectral hole in the same IBT.

To accumulate a spectral grating, we used pairs of optical pulses, $E_1^{(j)}(\tau)$ and $E_2^{(j)}(\tau)$, with pulse areas θ_1 and θ_2 , respectively, that are separated in time by an interval τ_{21} and applied to the IBT regularly every τ_R ($j = 1, 2, \dots$). To avoid coherent beating effects between consecutive pulse pairs, we use $\tau_R \geq 2T_M$, where T_M is the homogeneous dephasing memory time of the IBT. To minimize θ_1 , θ_2 , and the loss of grating strength over the decay duration ($\tau_R - \tau_{21}$), we use

$T_G \gg \tau_R \approx 2T_M$, where T_G is the effective lifetime of the grating.^{3,4}

Continuous programming of a spectral grating is a desirable innovation for achieving practical optical coherent transient processors. Several short-term persistent IBT's with other desirable material parameters are currently available, although no practical long-term persistent transition is currently known. The efficiency of an accumulated steady-state grating is relatively high; its strength is roughly half that of a perfect persistent grating (if such a grating were ever possible) and orders of magnitude higher than any currently known persistent transition. Further, continuous programming reduces the instantaneous power requirements of the programming pulses, typically by 1 to 2 orders of magnitude compared with those of single-shot programming.³

For accumulation of a spectral grating, a constant phase relationship between $E_1^{(j)}(\tau)$ and $E_2^{(j)}(\tau)$ must be maintained for all j within T_G . For a continuous-wave (cw) source that is crafted into programming pulses, the frequency jitter, $\delta\nu_0$, must satisfy $\delta\nu_0 \ll (1/2\tau_{\text{prog}})$ over T_G , where τ_{prog} is the total duration of a programming pulse pair.

The experimental demonstrations were performed in single-dipole Tm³⁺:YAG (0.1 at. %; absorption coefficient, $\sim 2 \text{ cm}^{-1}$), maintained at 4.5 K in a continuous-flow liquid helium cryostat. The cw output of an argon-pumped Ti:sapphire laser, resonant with the ³H₆-³H₄ transition of Tm³⁺ at 793.2 nm (upper-state lifetime $T_1 \sim 590 \mu\text{s}$, bottleneck lifetime $T_B \sim 11.8 \text{ ms}$; we measured $T_M \sim 25 \mu\text{s}$), was first directed toward a double-passed 80-MHz acousto-optic modulator that introduced necessary corrections for keeping the laser frequency locked to a transient spectral hole in the IBT in a separate 7-mm-long Tm³⁺:YAG crystal at 4.5 K. A full description of the locking system will be published separately, and a similar method of locking the frequency of an external-cavity diode laser to a spectral hole can be found in Ref. 7. An initial measurement of the stability when the laser was locked to a spectral hole established an upper limit of 13-kHz rms frequency jitter over 640 μs (measurement limited), compared with 400 kHz rms when the laser was locked to an external reference cavity.

The frequency-locked cw beam was crafted into pulses by a 125-MHz acousto-optic modulator, whose rf drive signal was digitally created by a 1-Gsample/s arbitrary waveform generator, permitting control of the amplitude, frequency, and phase of all the input pulses and creation of repeated sequences of pulse pairs. The extinction ratio was improved by deflection of the entire pulse sequence with another acousto-optic modulator toward another 15-mm-long sample focused to an $\sim 140\text{-}\mu\text{m}$ spot ($1/e^2$ diameter). After the cryostat, the output signal was incident on a silicon photodetector and was captured on a digitizing oscilloscope.

We performed experiments to demonstrate accumulation of a spectral grating for two cases: true-time delay and correlation signal processing. In both cases, all the optical pulses were applied collinearly, which eliminated the possibility of jitter effects in different path lengths as a result of vibrations of the mirrors. After a pair of optical pulses was repeated N times, the grating was probed with an optical pulse that stimulated an emitted signal, the strength of which represented the strength of the spectral grating.

Figure 1 shows the first three repetitions of the input pulse pairs used to accumulate the spectral gratings, as detected before the optical sample. Figure 1(a) corresponds to true-time-delay programming; Fig. 1(b), to pattern waveform programming. In all cases, each individual pulse or subpulse was 120 ns in duration. In Fig. 1(a) the two reference pulses in each pair were separated by $\tau_{21} = 800$ ns, and the pulse pairs were repeated every $\tau_R = 49.44 \mu\text{s}$, each at a power of 14 mW. After the pulse pair was applied N times, a single probe pulse with a power of 150 mW (not shown) was applied τ_R after the last programming pulse pair. In Fig. 1(b), each pair consists of a pattern waveform and a reference pulse, at power levels of 4.0 and 13 mW, respectively, where $\tau_{\text{prog}} = 4.20 \mu\text{s}$ and $\tau_R = 52.84 \mu\text{s}$. After N pulse pairs, a probe-data waveform with a power of 70 mW (not shown) was applied, stimulating the medium to emit the temporal correlation of the pattern and data. The pattern and data were made temporally identical, each being a biphasic 5-bit return-to-zero Barker code $\{+, +, +, -, +\}$ so that the emitted signal was a single autocorrelation peak with low sidelobes.

Figure 2 shows single-shot captures of the probe pulse and the emitted output signal for varying values of N , as detected after the optical sample. Figure 2(a) shows the output signals that resulted when we applied the input pulses in Fig. 1(a). The time scale is set for the case in which $N = 1$, and subsequent traces are offset by $(N - 1)\tau_R$. Figure 3(a) plots the strength of each signal peak versus the time in which the grating was probed. The total duration of the entire sequence of pulse pairs was limited to ~ 4 ms by the length of the digitized rf signals produced by the arbitrary waveform generator. Thus the gratings were not completely in steady state when probed. For comparison we show a simulation curve produced by integration of the optical Bloch equations for an optically thin sample, given the timing of the applied

pulses, the number of repetitions, and the material parameters, where $\theta_1 = \theta_2 = 0.068\pi$ as derived from the steady-state solution for a three-level system^{3,4} and taking into account complete coherence loss after each programming pair and population decay over τ_R . Similarly, in Fig. 2(b) we plot single-shot captures of the probe-data pulse and the emitted output signal for various values of N for the input pulses in Fig. 1(b). In these traces the input data pulse is evident, followed by spurious echo signals and then the emitted autocorrelation peak. Figure 3(b) plots the strength of each correlation peak versus the time when the grating was probed, along with a simulation curve, produced with $\theta_1 = 0.036\pi$ and $\theta_2 = 0.064\pi$, as derived from comparison of the intensities of these pulses with those from Fig. 1(a).

Each of these experiments shows good agreement between the simulation curves and data points over ~ 4 ms. Accumulation of a periodic grating [Figs. 1(a), 2(a), and 3(a)] is analogous to photon echoes from an accumulated grating,⁴ and observation of the stability necessary to achieve this result with the system was a necessary first step. Accumulation of a complex grating [Figs. 1(b), 2(b), and 3(b)] placed far greater demands on the laser frequency stability. Since τ_{prog} was $\sim 4 \mu\text{s}$ in this experiment, stability of ~ 12.5 kHz [e.g., $\delta\nu_0 \sim (1/20\tau_{\text{prog}})$] over the accumulation time of ~ 4 ms was required and achieved. In fact, when the Ti:sapphire laser was locked to its external reference cavity rather than to a spectral hole, the output signals either fluctuated dramatically or disappeared.

This work represents preliminary results that will lead to more-elaborate experimental demonstrations. The next steps are to study the probe saturation effects and to work with three independent beams, for which continuous programming occurs asynchronously and simultaneously with processing. Gratings that perform adaptive processing in response to changes in the programming pulses could be demonstrated. A technique for writing a grating quickly with

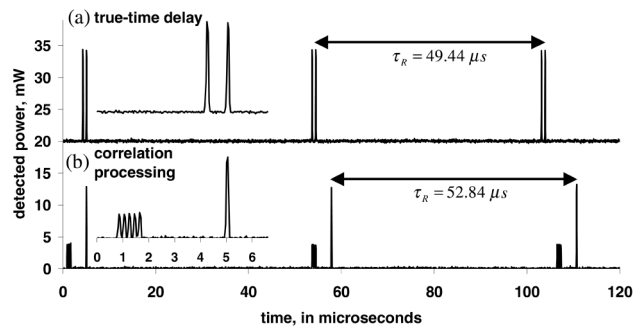


Fig. 1. Input pulses for continuous programming of a spectral grating by accumulation. Two programming pulses are repeated N times. (a) True-time-delay grating: two brief (120-ns) reference pulses, separated by 800 ns, program a periodic grating representing a true-time delay. (b) Pattern waveform grating: a pattern (120 ns per bit) and a brief reference pulse, separated by $4.2 \mu\text{s}$, program a complex grating representing that pattern and time delay. The 5-bit pattern $\{+, +, +, -, +\}$ was modulated in amplitude and phase.

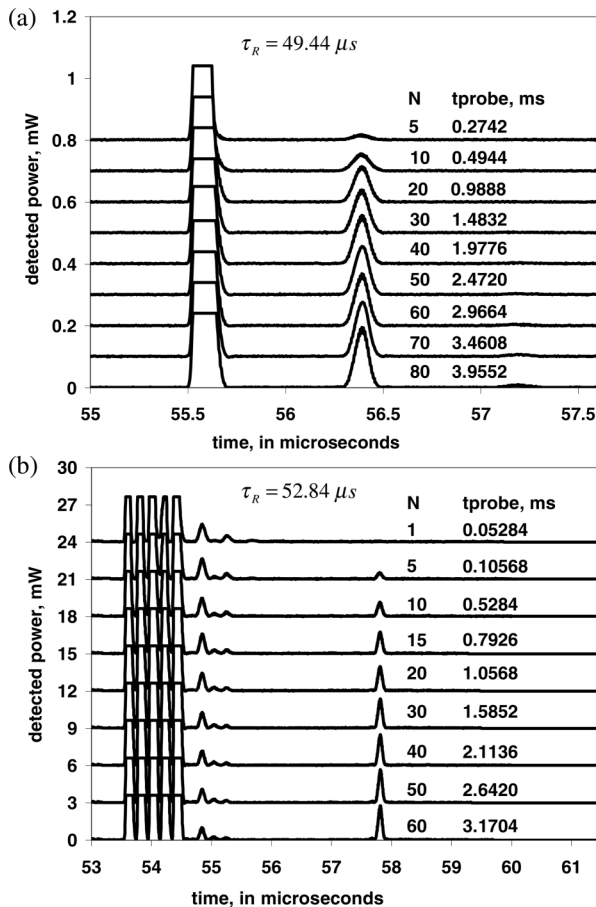


Fig. 2. Emitted output signal from an accumulated grating as a function of the number of times, N , that the programming pulse pairs were repeated. (a) True-time delay: the single probe pulse is shown on the left, followed by the true-time-delay emitted signal on the right. (b) Correlation signal processing: the applied pattern probe pulse is on the left, {+, +, +, -, +}, followed by spurious echo signals and then the autocorrelation peak of the data with the stored pattern.

higher-power pulses and then maintaining that grating with lower-power pulses should be demonstrated,³ along with the ability to erase and quickly rewrite new gratings.⁸

In summary, we have experimentally demonstrated the ability to accumulate a complex spectral grating, using optical pulses crafted from a cw frequency-stable optical source. The spectral grating represented either a pure true-time delay or a time delay and an amplitude- and phase-modulated waveform. This study is a step toward development of an optical coherent transient device that maintains a grating in a short-term persistent transition such as that at 793.2 nm in Tm:YAG at 4.5 K. Such a device has the potential to provide, for example in the control of complex array antennas, correlation of a multigigahertz continuous data stream with a large time-bandwidth pattern and to impose a variable high-resolution true-time delay⁶ of up to several microseconds on the results.

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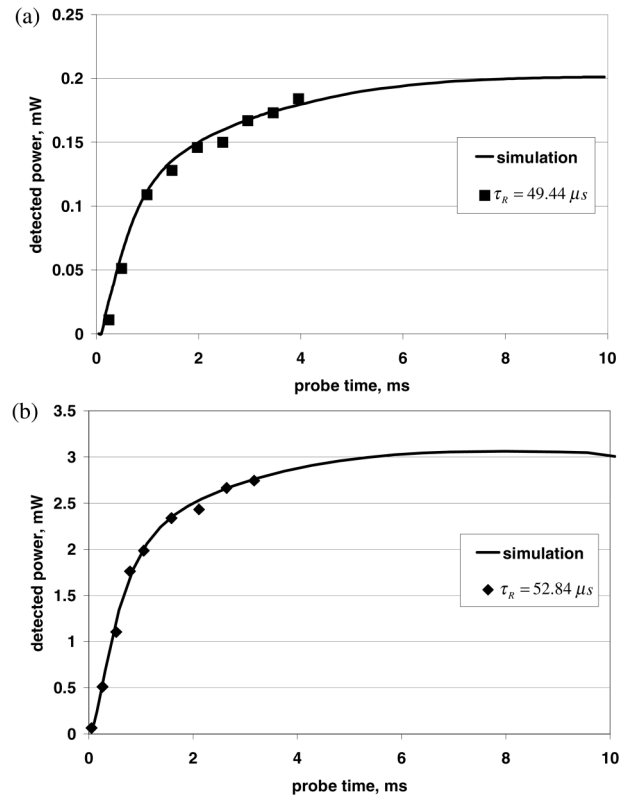


Fig. 3. Plots of the peak power of the emitted echo signals in (a) Fig. 2(a) and (b) Fig. 2(b) versus the time that the grating was probed, showing the dynamics of the spectral grating buildup toward steady state. Simulated curves are also shown for an optically thin sample.

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