A novel technique for continuously programming an optical coherent transient spatial–spectral signal processor is proposed. The repeated application of two spatially distinct optical programming pulses to a nonpersistent hole-burning material writes an accumulated spatial–spectral population grating. An optical data stream is introduced on a third beam, resulting in a processor output signal that is spatially distinct from all the input pulses. Programming and processing take place simultaneously, asynchronously, and continuously. In the case of true-time delays, the efficiency that is achievable with currently available materials is of the order of that predicted for a perfect photon-gated device.

In general, an OCT processor is programmed with two temporally modulated optical pulses that are separated in time and resonant with an IBT. Each laser pulse has a form $E_n(t-t_s-\eta_n)\cos[\omega_0(t-\eta_n)+\phi_n]$, where the subscript $n$ determines the order of arrival of each pulse, $E_n(\tau)$ is a slowly varying temporal envelope function, $\omega_0$ is the laser center frequency, $\eta_n=(k_n \cdot r/c)$, where $k_n$ is the unit wave vector of pulse $n$, $\phi_n$ is the phase of pulse $n$, and each pulse reaches the medium at $r=0$ at its arrival time $t_n$. The two waveform envelopes, $E_1(\tau)$ and $E_2(\tau)$, separated by $\tau_{21}=t_2-t_1$, cause a spatial–spectral holographic population grating on the IBT. A programming pulse can be a temporally brief reference pulse (BRP), a linear frequency-chirped reference pulse, or a TSW that represents data.

After a grating is programmed, the atomic absorption is selective in both frequency and space for subsequently applied optical waveforms. As long as the grating survives, a subsequently applied $E_3(\tau)$ causes a coherent emission $E_s(t-t_s-\eta_s)\cos[\omega_0(t-\eta_s)+\phi_s]$ from the IBT with the temporal envelope of the form

$$E_s(t-t_s-\eta_s) \propto \int_{-\infty}^{\infty} E_1^*(\Omega)E_2(\Omega)E_3(\Omega) \exp[i\Omega(t-t_s-\eta_s)]d\Omega, \quad (1)$$

where $t_s=t_3+t_2-t_1$, $\eta_s=\eta_3+\eta_2-\eta_1$, $\phi_s=\phi_3+\phi_2-\phi_1$, and $E_n(\Omega)$ is the Fourier transform of the $n$th applied optical waveform envelope, $E_n(\tau)$. Relation (1) is based on the Fourier transform approximation of the input waveforms, valid when these bandwidths less than the inhomogeneous linewidth, $\delta\omega_1$, and intensities that ensure a linear response, avoiding both coherent and incoherent saturation.
The phase-matching condition for the proposed continuous processing and programming technique is \( k_s = \tilde{k}_3 + k_2 - k_1 \), where all three input pulses are distinct such that \( k_1 \neq k_2 \neq k_3 \). Figure 1(a) shows a three-dimensional representation of this scheme. Perfect phase matching is achieved if the pulses are directed such that for a given vector \( k_0 \), the individual wave vectors are \( \tilde{k}_2 = k_0 + \delta k_0 \), where for \( n = 1, 2, 3 \), every \( |\delta k_n| \) is equal, \( \delta k_2 \perp k_0 \), and \( \delta k_3 = -\delta k_0 \). In addition, we achieve phase-matched angular multiplexing by varying \( \delta k_1 \) while maintaining the above conditions.

The complete spatial–temporal implementation of the input pulses is shown in Fig. 1(b), for the specific case of signal cross correlator. In this schematic a pair of programming pulses \( E_1(\tau) \) and \( E_2(\tau) \) is repeated at regular intervals \( \tau_R \). In this case, the first (second) programming pulse is a TSW (BRP) on beam 1 (beam 2). Once the grating is accumulated, the waveform to be processed can be propagated along beam 3. Here the programmed pattern is included twice in this waveform. Figure 1(c) shows the shape and timing of the resulting output signal emitted along \( \tilde{k}_3 \) with respect to the third pulse after it exits the medium. Here this signal consists of two autocorrelation peaks and other correlation signals, provided that the accumulated grating is saturated.

One must satisfy certain conditions to obtain efficient processing. First, consider the programming timing limitations with respect to material parameters. We define a generalized three-level system in which the radiation field couples only states \( |1\rangle \) and \( |2\rangle \) and there is an intermediate state \( |3\rangle \), with population relaxation times \( \kappa_{21}^{-1} \), \( \kappa_{23}^{-1} \), and \( \kappa_{31}^{-1} \) between the numbered states. This system reduces to a two-level system if \( \kappa_{23} = 0 \). The upper- and intermediate-state lifetimes are \( T_1 = (\kappa_{21} + \kappa_{23})^{-1} \) and \( T_2 = \kappa_{31}^{-1} \). In general, the quantity \( (\tau_2 + \delta \tau_1 + \delta \tau_2) \) is limited by the homogeneous dephasing time, \( T_2 \). The inclusion of pulse duration \( \delta \tau_n \) of pulses 1 and 2 accounts for the general case in which \( \delta \tau_n \ll \tau_2 \) is not satisfied. Requiring that \( T_2 \geq 40(\tau_2 + \delta \tau_1 + \delta \tau_2) \) makes the loss of efficiency that is due to coherent decay less than 10%, although techniques exist to compensate for this loss.9 Setting \( \tau_R \approx 2T_2 \) avoids coherent interference between successive pairs of programming pulses. Setting \( \tau_R \) much less than \( T_2 \), the greater of \( T_1 \) or \( T_2 \) ensures that the repeated programming pulse pairs at the appropriate intensity form an accumulated grating,8 where after reaching steady state, their application exactly compensates for the relaxation losses during \( \tau_R \). The relaxation losses during \( \tau_R \) cause a fractional drop in the intensity of the output signal, \( \varepsilon \). For \( \varepsilon \) to be small, \( \tau_R \) must be chosen appropriately.

Beyond the population decay dynamics, the stability of the optical source is an important consideration, analogous to the discussion in Ref. 10. In practice, each repeated programming sequence may not be identical. The stored grating from a single pair of programming pulses, \( G(\Omega) \propto E_1^*(\Omega)E_2(\Omega) \times \exp\{i(\Omega\tau_21 + \phi_{21})\} \times \text{c.c.} \), depends on the phase difference \( \phi_{21} = \phi_2 - \phi_1 \) between the two pulses. This phase difference can fluctuate owing to short-term frequency drift of the optical carrier. If the carrier frequency changes to \( (\omega_0 + \delta \omega_0) \), a change in the phase difference between the programming pulses of \( \delta \phi_{21} = \delta \omega_0 \cdot \tau_21 \) will result. Consider any two programming pulse pairs, labeled the \( j \)th and the \( k \)th pairs, that occur within a time shorter than \( T_G \). If \( \phi_{21} \) differs from \( \phi_{21}^{\text{ref}} \) by roughly \( \pi \), then the pulse pairs’ contribution leads to incoherent accumulation of the grating and ineffective processing. The requirement exists, therefore, that \( [\phi_{21}^{\text{ref}} - \phi_{21}^{(j)}] \ll \pi \), implying that the short-term laser frequency stability should follow \( \delta \omega_0 \ll \pi/(\tau_21 + \delta \tau_1 + \delta \tau_2) \) over any time period \( T_G \). When a single optical source creates the programming and processing beams, its long-term frequency drift is inconsequential, provided that all pulse bandwidths stay well within \( \delta \omega_0 \). As the laser drifts, the previous grating decays and the new grating seamlessly accumulates when the above condition is maintained.

Assuming a stable optical source, a continuously programmed continuous processor has the ability to produce a highly efficient grating. For continuously programmed memories and processors, when pulse 1 or 2 is a TSW, optimizing the efficiency must be balanced with nonlinearities that lead to signal distortion. But for the case of a true-time delay device when the first two pulses are both BRP’s,
the efficiency analysis follows from the treatment of accumulated gratings described in Ref. 8, in which the steady-state population solutions were derived for a three-level system. For an absorber at frequency \( \omega \), the steady-state spectral population difference between the excited and the ground states is

\[
\omega(\Delta) = (1 - p) \frac{\exp(-x_1)[1 - \exp(-x_p)] + \beta[\exp(-x_B) - \exp(-x_1)]/2}{1 - \exp(-x_B) - p \exp(-x_1)[1 - \exp(-x_B)] + \beta(1 - p)[\exp(-x_B) - \exp(-x_1)]/2 - 1}, \tag{2}
\]

where \( \Delta = \omega - \omega_0 \), \( \beta = \kappa_{23}/(\kappa_{23} + \kappa_{31} - \kappa_{31}), \) \( x_B = \tau_R/T_B, \) \( x_1 = \tau_R/T_1, \) and \( p = 1 - 20^2 \cos^2(\Delta T_21/2 + \phi_{21}) \), assuming that \( \theta_1 = \theta_2 = \theta \), where \( \theta_3 \) is the area of pulse \( n, \theta \leq 0.1 \pi \) and \( \tau_{21} \ll \tau_2 \). Equation (2) reduces to the two-level case when \( \beta = 0 \).

A qualitative estimate of the intensity of the true-time delay output signal is the magnitude squared of the inverse Fourier transform of Eq. (2), evaluated at \( \tau_{21} \). For reference, the efficiency is normalized against that of a photon-gated two-level persistent hole-burning system with gating efficiency \( \gamma_{\text{gate}} = 1.3 \). In general, given fixed values for \( T_1, T_B, \) and \( \beta \), we can optimize the efficiency to \( \eta_{\text{opt}} \) for any given \( \tau_R \) by varying \( \theta \) to a value \( \theta_{\text{opt}} \). Increasing \( \tau_R \) increases both \( \theta_{\text{opt}} \) and \( \epsilon \). It is found that \( \eta_{\text{opt}} \) is identical for all \( \tau_R \) and \( \eta_{\text{opt}} = 0.47 \). Thus, nonpersistent materials can have efficiencies higher than that of a photon-gated material with \( \gamma_{\text{gate}} < 0.68 \), since the output intensities of gated systems go as \( \gamma_{\text{gate}}^2 \). Currently available gated materials have \( \gamma_{\text{gate}} \ll 1 \), so in comparison with these the efficiency of a continuously programmed grating is several orders of magnitude greater. For \( T_B \gg T_1 \), the efficiency is due almost entirely to the first harmonic of the accumulated grating in the ground state, not the upper state. For \( \beta = 0 \) or for \( T_B \ll T_1 \), both ground- and upper-state population gratings contribute to the efficiency.

Consider two nonpersistent material system that are currently available at wavelengths compatible with commercially available diode lasers. For a three-level system, \( T_m^{10} \):YAG (0.1 at. %) offers an intermediate bottleneck level between the two levels of the IBT at 793 nm. At 4.4 K, \( \delta \omega_l = 17 \text{ GHz}, T_2 \sim 16 \mu s, T_1 \sim 800 \mu s, T_B \sim 9 \mu s, \) and \( \beta = 0.59 \). Setting \( \tau_R = 32 \mu s \) yields \( \theta_{\text{opt}} = 0.05 \pi \) and \( \epsilon = 2.0 \). Delays of up to 0.4 \( \mu s \) are feasible without any compensation,\(^9\) provided that the laser frequency is stable to 250 kHz over 9 ms. For a two-level system, Er\(^{3+}\):LiNbO\(_3\) (0.06 at. %) has an IBT at 1.53 \( \mu \text{m.} \) At 1.6 K, \( \delta \omega_l = 200 \text{ GHz}, T_1 \sim 10 \text{ ms} (\beta = 0), \) and \( T_2 \sim 40 \mu s \) in a 3-kG external magnetic field.\(^{13}\) Setting \( \tau_R = 80 \mu s \) yields \( \theta_{\text{opt}} = 0.045 \pi \) and \( \epsilon = 1.6 \%. \) Delays of over 1.0 \( \mu s \) are feasible for a laser that is stable to 100 kHz for 10 ms. For both cases the efficiencies are still better than that of a gated material with \( \gamma_{\text{gate}} < 0.68 \).

This analysis and the predicted efficiencies are valid for the OCT true-time delay regenerator\(^5\) programmed with BRP’s as well as with frequency-chirped reference pulses.\(^6\) The input beam geometry has the benefit that nonlinearities introduced by the multiple programming stages do not lead to harmonics of the delay in the output signal direction in the case of true-time delay regenerators.

In summary, we have proposed a novel OCT technique for programming and processing. Utilizing distinct processing and programming beams makes it possible to simultaneously program a grating while asynchronously processing a continuous waveform against it. New delays or patterns can be reprogrammed into the material in a time roughly equal to the greater of \( T_B \) or \( T_1 \). This technique alleviates the need for photon gating in several types of OCT devices, specifically optical dynamic random-access memory, waveform cross correlators, and true-time delay regenerators. Multigigahertz, efficient, real-time processing with large-bandwidth products (\( > 10,000 \)) can be achieved in currently available nonpersistent materials.

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