

Temporally overlapped linear frequency-chirped pulse programming for true-time-delay applications

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A novel technique for programming broadband true-time delays that uses two frequency-offset temporally overlapped linear frequency-chirped pulses to produce periodic spectral gratings in an inhomogeneously broadened absorber is presented. Advantages of this technique include its ability to use chirped pulses that are longer than the coherence time of the crystal, less stringent laser frequency-stability requirements for grating accumulation, lower power requirements, a simplified system design, and the ability to tune broadband (multigigahertz) delays over a wide dynamic range (picoseconds to microseconds). © 2002 Optical Society of America

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Spatial spectral holography (or stimulated photon echoes) has been proposed as the basis for many high-bandwidth optical devices such as low-latency memory systems, signal correlators, signal processors, and broadband true-time-delay (TTD) systems for phased array antennas.¹⁻⁴ Most of these applications have been developed and demonstrated at low bandwidths, limited by the capabilities of acousto-optic modulators used. Achieving higher-bandwidth operation requires developing practical methods for programming efficient high-bandwidth gratings into inhomogeneously broadened absorbers (IBAs). To mitigate laser power limitations and crystal damage thresholds, two techniques have been proposed for TTD programming: accumulation and linear frequency-chirped (LFC) programming pulses.^{5,6}

Accumulation involves repeated application of programming pulses to build up and maintain efficient spectral gratings. It allows much lower-power lasers to be used to create efficient gratings than when a single programming pulse pair is used to create the gratings, but it does put different frequency-stability requirements on the programming pulses.^{5,7} The most stringent requirement is that the phase difference between the pulses that make up each pulse pair vary much less than π between two coherently accumulated gratings. This requires that the frequency of the laser jitter be much less than the reciprocal of the programmed TTD (up to a few milliseconds) over the grating lifetime (typically milliseconds).

A LFC pulse is one whose instantaneous frequency varies linearly from the beginning to the end of the pulse. When a pair of temporally separated LFC pulses illuminates an IBA, such as a rare-earth ion-doped crystal, the ions record the separation between the times when the instantaneous frequencies of the first and second LFC pulses match the ion's resonant frequency, resulting in a periodic spectral grating in the IBA with a period equal to the reciprocal of the time separation. Programming with LFC pulses instead of brief pulses has the advantage of spreading the spectral energy of the pulse over a longer duration and thus producing efficient gratings with much lower peak powers of the programming pulses.

Programming TTD gratings with two LFC pulses has the added advantage that one can tune the programmed delay by simply adjusting the start frequencies of the LFC pulses. As was previously demonstrated,⁴ a TTD grating can be set up with two LFC programming pulses, each with the same chirp rate, γ , as shown in Fig. 1(a). These LFC pulses, each of temporal length τ_c and bandwidth $B = \gamma\tau_c$, are separated by a delay, τ_{21} . In the simple case that both LFC pulses start out with the same frequency, the delay programmed, τ_D , is equal to τ_{21} . However, if there is a difference in the start frequency between the two pulses, the programmed delay can be shifted. The programmed delay is then given by⁶

$$\tau_D = \tau_{21} + \delta/\gamma. \quad (1)$$

If $\gamma > 0$, δ is defined as the start frequency of the first LFC pulse minus the start frequency of the second

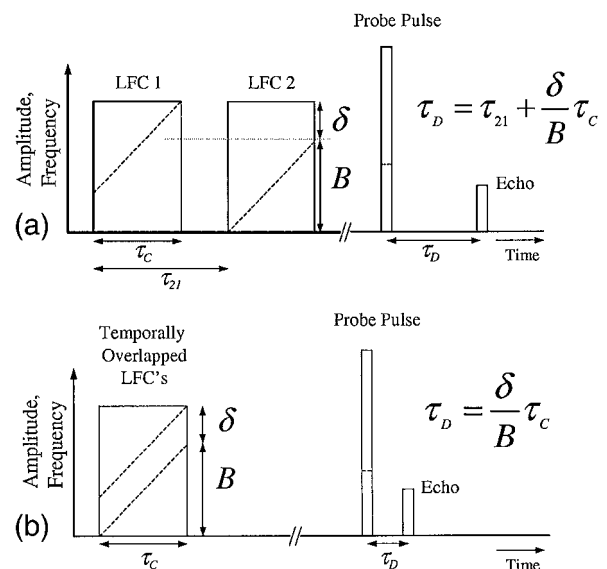


Fig. 1. Input sequences and expected echo as a function of the frequency offset between (a) two LFC pulses separated by a delay τ_{21} and (b) two temporally overlapped LFC pulses. Solid lines, amplitude; dashed lines, frequency.

LFC pulse. The bandwidth of the probe pulse signal should not be greater than the overlap of the two LFC pulses' bandwidths. This technique has great promise for TTD applications because one can shift the time delay simply by changing the offset between the start frequencies of the LFC pulses. Delay times of several microseconds have been programmed with errors in delay accuracy of less than 100 ps.⁶

Whereas there are significant advantages in using LFC pulses rather than brief pulses for programming TTD gratings, there are several drawbacks in the above approach. First, the two LFC pulses must be completed within the dephasing time, T_2 , to produce efficient gratings. Thus the duration of the individual LFC pulses must be less than T_2 (typically a few microseconds). For high bandwidth, extremely high chirp rates (several gigahertz per microsecond) are required, putting unrealistic demands on the LFC source. Also, the power required for efficiently programming an IBA is proportional to B/τ_C . Thus, limited LFC pulse duration translates to higher power requirements as the bandwidth increases. The next drawback comes from the fact that in practice $\delta \ll B$ to utilize most of the LFC bandwidth.⁶ Thus the tunable range of delay times is limited to much less than the LFC pulse duration (much less than T_2). Finally, to accumulate a spectral grating requires that the phase relationship between the two LFC pulses be constant for all the programming sequences within the grating lifetime. The minimal requirement is that the frequency jitter of the laser, Δf , satisfy $\Delta f \ll 1/2\tau_D$.⁵ Such stability, whereas it is achievable for single-frequency laser sources, is extremely difficult to achieve with LFC laser sources.

The approach proposed here is based on the realization that the two LFC pulses need not be temporally separated but can overlap in time, even to the point when $\tau_{21} = 0$, as shown in Fig. 1(b). If $\tau_{21} = 0$, the two LFC pulses can be derived from the same LFC source, where a frequency offset between the two LFC pulses is introduced by low-bandwidth acousto-optic modulators (AOMs) driven at different radio frequencies. This technique has several advantages: The programmed TTD of the grating is now directly proportional to the frequency offset between the two programming LFC pulses. The LFC pulse duration can now far exceed T_2 , as long as the delay programmed is less than T_2 . Programmed delays can now be tuned from hundreds of picoseconds to microseconds. The power requirement on the LFC pulses is reduced by roughly a factor of τ_C/T_2 . The stringent phase requirement for accumulation is reduced to a chirp linearity requirement on the LFC source. And, finally, the overall system design is simplified.

A low-bandwidth (40-MHz) single-shot (no accumulation) experimental verification of temporally overlapped LFC pulse programming was carried out on the 793.39-nm 3H_6 - 3H_4 transition of 0.1% Tm^{+3} :YAG cooled to 4 K with an absorption length of 1.4. An external-cavity diode laser was used as the laser source amplified with injection locking. Two AOMs were used in series to create the temporally

overlapped LFC pulses. The first AOM created a LFC pulse with $B = 40$ MHz. The second AOM was driven by the voltage

$$V = A\{\cos[2\pi(f_m - \delta/2)t] + \cos[2\pi(f_m + \delta/2)t]\}, \quad (2)$$

resulting in two LFC pulses with different frequency shifts. Here f_m is the center frequency of the AOM, δ is the offset frequency, and A is the amplitude. The light was focused tightly into the second AOM to keep the angle between the two frequencies close to the diffraction limit, ensuring spatial overlap of the two frequency-offset pulses. The same AOMs created the probe pulse (with $\delta = 0$). The power of the collinear pulses before they were focused into the crystal was 35 mW, and the beam waist diameter was ~ 35 μm . The output from the crystal was incident upon a 1-GHz silicon photodiode and recorded on a digitizing oscilloscope with a bandwidth of 300 MHz. The crystal's T_2 was measured to be approximately 15 μs , likely limited by excitation-induced spectral diffusion.

The time between single-shot experiments was made much greater than the grating lifetime to eliminate shot-to-shot interference. The temporally overlapped LFC programming pulses were followed 35 μs later by a 50-ns probe pulse, generating a delayed echo output. We tuned τ_D by changing frequency offset δ for various values of τ_C to demonstrate the wide tunability of the programmed TTD. In Fig. 2 the observed delay of the echo, τ_D , is plotted versus offset frequency δ for several temporal chirp lengths, $\tau_C = 0.5, 1, 3, 5, 15, 30, 100$ μs . The observed delay matches the delays calculated from Eq. (1) (solid curves). It is important to note that echo outputs were observed for $\tau_C = 30$ and 100 μs , showing that τ_C can be considerably longer than T_2 . Figure 3 shows the results of a TTD for an amplitude-modulated probe pulse. The probe, a binary coding of 101011001 at a rate of 20 Mbits/s, was sent into the crystal 40 μs after the programming LFC pulses with $\tau_C = 100$ μs and $\delta = 0.25$ MHz. The echo signal was delayed by

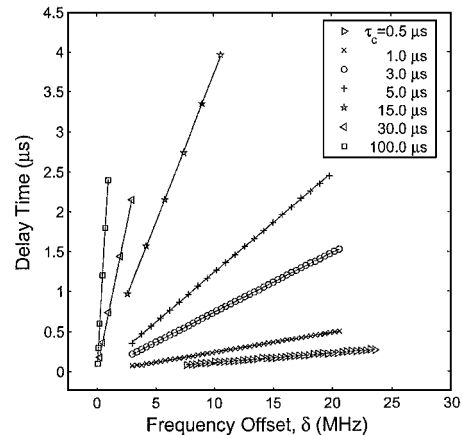


Fig. 2. Measured echo delays versus frequency offset for several values of τ_C ; solid lines are calculated from Eq. (1). The lines for $\tau_C = 30$ and 100 μs demonstrate LFC pulse durations well in excess of T_2 .

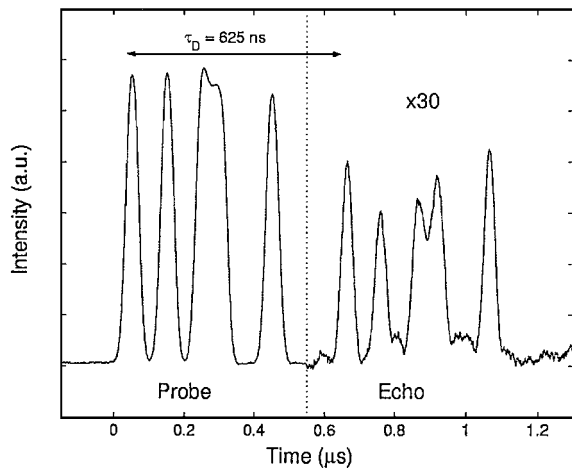


Fig. 3. Example of a TTD data sequence (right, $\times 30$). Here $\tau_c = 100 \mu\text{s}$, with a programmed time delay of 625 ns. The data sequence (left) is 101011001 at a data rate of 20 Mbits/s.

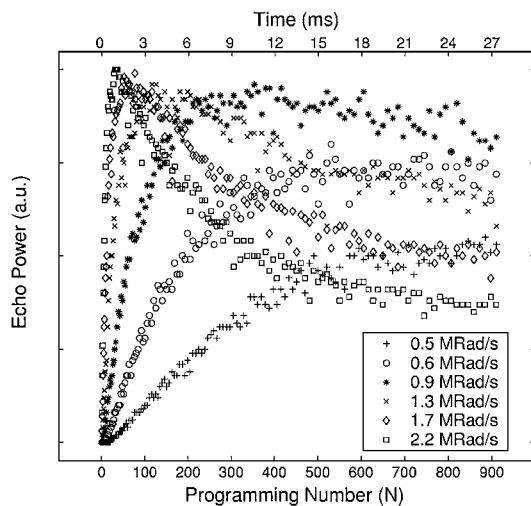


Fig. 4. Echo powers versus programming number (lower axis) and time (upper axis) for a frequency-stabilized Ti:sapphire laser system. Various programming strengths (Rabi frequency, Ω) are plotted, as shown in the legend. Here $\tau_c = 1 \mu\text{s}$, $\tau_D = 250 \text{ ns}$, and $\tau_r = 31 \mu\text{s}$.

the expected $\tau_D = 625 \text{ ns}$. Good signal fidelity as well as strong echo efficiency ($\sim 2.5\%$) has been achieved.

To demonstrate accumulation with temporally overlapped LFC pulses we used a frequency-stabilized Ti:sapphire laser that was locked to a regenerative spectral hole, resulting in a laser jitter of a few kilohertz.⁵ We studied the buildup and maintenance dynamics of the accumulated gratings^{5,7} by varying the strength of the LFC pulses as characterized by the LFC pulses' Rabi frequencies. The Rabi frequencies $\Omega = 0.5, 0.6, 0.9, 1.3, 1.7, 2.2 \text{ mrad/s}$ were derived from observations of the optical nutation produced when the pulses were not chirped. The programming LFC pulses were repeated N times with a repetition time τ_r of $31 \mu\text{s}$. After the N programming sequences, the grating was probed with a 50-ns brief

pulse, as in the single-shot experiments. Figure 4 details the echo peak power as a function of N for each programming pulse strength. For this figure, $\tau_c = 1 \mu\text{s}$ and $\delta = 10 \text{ mrad/s}$, yielding a delay time for the echo of $\tau_D = 250 \text{ ns}$. For the weaker programming strengths, $\Omega \leq 0.6 \text{ MHz}$, the repeated programming pulses cannot accumulate an efficient grating before population decay sets in. An interesting aspect of the larger programming strengths, $\Omega \geq 1.3 \text{ mrad/s}$, is that the programmed grating peaks quickly and then saturates, leading to inefficient gratings. Between these two regimes, the best steady-state accumulation can be found at the $\Omega = 0.9 \text{ mrad/s}$ programming strength.

In this Letter we have demonstrated that frequency-offset temporally overlapped linear frequency chirps can program efficient TTD gratings in inhomogeneously broadened absorbers. Both single-shot and accumulation experiments were performed. The advantages of this technique compared with other techniques are (1) its ability to use chirps longer than the coherence time of the crystal, (2) relaxed laser requirements, (3) lower power requirements, (4) its ability to produce broadband delays over a wide dynamic range, and (5) a simplified system design. The $0.1\% \text{ Tm}^{3+}:\text{YAG}$ crystal used in these experiments had a 17-GHz inhomogeneous bandwidth, but the demonstrated bandwidth was limited by the LFC source used. Broadband chirped sources are becoming available,⁸ and by combining them with a low-bandwidth frequency shifter (an acousto-optic modulator), we can tune high-bandwidth (multigigahertz) true time delays from picoseconds to microseconds.

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