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Coherent transient data-rate conversion and data transformation

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Temporal compressions of optical pulses and pulse trains have been performed by the photon-echo process in Tm-doped YAG at 793 nm. Single-pulse temporal compression by almost a factor of 500 from 10 μs to 22 ns and pulse train compression by a factor of 14 from 5 μs to 350 ns with a high-speed frequency-tunable external-cavity diode laser are demonstrated. It is suspected that significantly higher compression could be obtained by improved control of the laser frequency and laser frequency chirps. Theoretically, Tm-doped YAG should be capable of compressing single pulses by almost a factor of 10^7.

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At present there is a large amount of activity directed toward investigating and developing the potential of photon echoes for all-optical data storage and all-optical data processing applications. Further, because in the photon-echo technique it is the frequency Fourier transform of the temporal data that is stored, the technique offers unique possibilities for all-optical processing of temporal data.

All-optical operations on temporal signals can also be performed with combinations of gratings and prefabricated masks.[1] With respect to these techniques, time-domain operations in which photon echo materials are used differ in the sense that they can be reprogrammed during the experiment instead of being limited to only one fixed type of operation. With photon-echo techniques it is also possible to all-optically modify and tailor temporal signals in the microsecond–nanosecond region, i.e., with submegahertz or kilohertz frequency resolution.

We propose that a potential application for this type of time-domain processing that uses photon echoes would be to work at the upper rate limit for electronic devices and then to compress data in time and thereby increase the data rate by using a photon-echo process. The compressed data could propagate through a high-speed transmission link and then be stretched in time in a second photon-echo process such that they could again be read by electronic devices. The energy efficiency in the photon-echo process is in most cases low. Such a scheme would therefore probably also require amplification of the output from the initial photon-echo data compression step[2] before the photon-echo data stretching operation took place.

Spurred by exciting prospects such as those discussed above, we have, building on previous studies by other groups of researchers,[3–5] pushed to achieve improved performance in photon-echo single-pulse and multibit data compression. Here we discuss single-pulse compression by a factor of 450 from 10 μs to 22 ns and present an example of multibit compression by a factor of 14. It is interesting to note that, when the chirp interval is much larger than the bandwidth of a single unchirped bit, the mathematical description of temporal multibit compression is equivalent to the mathematical description of transverse diffraction in space by a multiple-slit pattern in the Fraunhofer approximation. Even though this effect was not, to our knowledge, pointed out explicitly before, the issue of space–time duality in photon echo processes is well known; see, e.g., Refs. 6 and 7.

An external-cavity diode laser equipped with an intracavity electro-optic crystal was used in this experiment. We could linearly chirp the laser frequency of this external-cavity diode laser over large intervals by supplying voltage ramps to the electro-optic crystal. This construction is based on the design by Mossberg and co-workers.[8] The laser was operated in single mode and tuned to the $^3H_4$–$^3H_6$ transition line of the trivalent rare-earth ion Tm^{3+} doped in YAG at 793.1 nm. The laser output power was ~30 mW with a short-time linewidth of ~350 kHz over a period of 200 μs. We measured this linewidth by first irradiating the sample at a fixed frequency and then observing the width of the hole burned in the absorption profile by applying a voltage ramp to one of the acousto-optic modulators and scanning laser frequency across the hole. The pulses in the compression sequence were created by acousto-optic modulators AOM1 and AOM2 (Isomet Corporation, Model 1205C). The 0.1 at.% Tm-doped YAG crystal was 5 mm thick along the direction of light propagation, and it was submerged in liquid helium. The laser spot (~2 mm in diameter) was focused onto the crystal by a 10-cm focal-length lens. An additional acousto-optic modulator (AOM3) was inserted at the detection side between the crystal and a photomultiplier tube to reject the excitation pulses transmitted through the crystal.

The recorded data were compared with analytical and numerical calculations of the photon echo time-compression process. Schematic pictures of the input pulse frequencies and intensities for the single-bit and multibit compression experiments are shown in Fig. 1. The electromagnetic fields of the first pulse (or, alternatively, of the pulse sequence) and of the second pulse are denoted E_1 and E_2, respectively. The echo output field as a function of time, $E_e(t)$, equals the first input field $E_1(t)$ correlated with the second field $E_2(t)$ convoluted with itself i.e.,

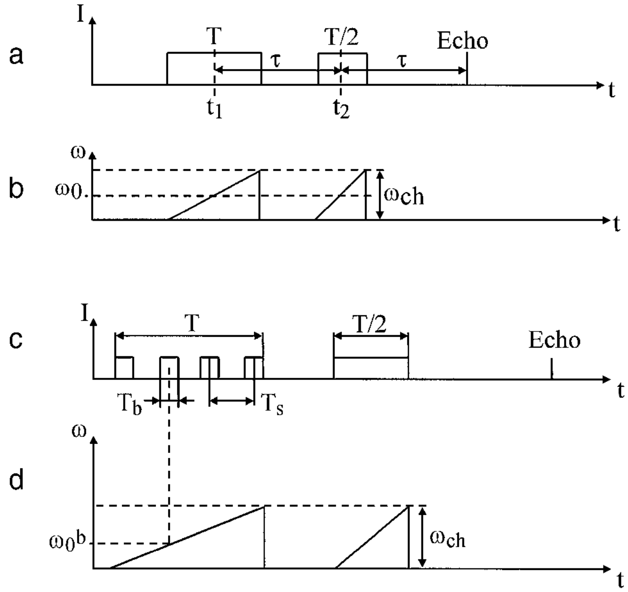

Fig. 1. a, Input intensity and b, frequency as functions of time for single-pulse compression. The excitation pulses are centered about times t_1 and t_2. ω_0 is the center frequency of the frequency chirp. The echo occurs at the times indicated by the vertical lines. In c and d the input parameters are shown for multibit compression. $\omega_0{}^j$ is the center frequency for input bit j.

$$E_e(t) \propto \int_{-\infty}^{\infty} E_1{}^*(\omega)E_2{}^2(\omega)\exp(i\omega t)\mathrm{d}\omega\,, \tag{1}$$

where $E_i(\omega)$ is the frequency Fourier transform of $E_i(t)$. We consider two chirped excitation pulses, of lengths $T_1 = T$ and $T_2 = T/2$, as in Fig. 1a. Assume that both excitation pulses are chirped over the bandwidth ω_{ch} and that $\omega_{\mathrm{ch}}T \gg 1$. Within the time interval $t \in [t_i - T_i/2,\ t_i + T_i/2]$ we write the electric field of pulse i as $E_i(t) = \exp\{-i[\omega_0 + K(t - t_1)](t - t_i)\}\exp - (i\mathbf{k}_i \bullet \bar{r})$, where $K = \omega_{\mathrm{ch}}/(2T_i)$. The echo will now appear in the direction $\mathbf{k}_e = 2\mathbf{k}_2 - \mathbf{k}_1$ at time $t_e = 2t_2 - t_1$. Graf *et al.*[5] suggested that, in the regime $\omega_{\mathrm{ch}}T \gg 1$, the excitation pulses can be regarded as constant in the frequency interval $[\omega_0 - \omega_{\mathrm{ch}}/2,\ \omega_0 + \omega_{\mathrm{ch}}/2]$ and zero otherwise. Relation (1) can then be simplified as

$$E_e(t) \propto \int_{\omega_0-\omega_{\mathrm{ch}}/2}^{\omega_0+\omega_{\mathrm{ch}}/2} \exp(i\omega t)\mathrm{d}\omega = \exp(i\omega_0 t)\omega_{\mathrm{ch}} \times \mathrm{sinc}\left(\frac{\omega_{\mathrm{ch}}}{2}\, t\right), \tag{2}$$

where we now have chosen zero for the time axis such that the echo occurs at time $t_e = 0$. The full width at half-maximum for the intensity of this echo pulse is approximately $T_e = 5.5/\omega_{\mathrm{ch}}$. If the duration of the first pulse is T_b, where $T_b \le T$ and the chirp rate is kept unchanged, we can still use the result above if we replace ω_{ch} with $\omega_{\mathrm{ch}}{}^b$ [where $\omega_{\mathrm{ch}}{}^b = \omega_{\mathrm{ch}}(T_b/T)$]. Numerical and analytical calculations show that this result holds as long as $\omega_{\mathrm{ch}}T_b \gg 1$. The results above can now be used to analyze the compression of a sequence of data bits. We therefore consider the first pulse with time duration T to consist of several bits of duration T_b that have their center points separated by a time T_S (Fig. 1c). If only $\omega_{\mathrm{ch}}T_b \gg 1$, the echoes of the separate bits will all appear at the same time. To get the resultant echo field it is then sufficient to sum the echo fields from all the individual bits. (If $\omega_{\mathrm{ch}}T_b \ll 1$ and $\omega_{\mathrm{ch}}T \gg 1$ the first pulse will work as a brief pulse and the echo will have duration T.) Summing the echo output field for several individual bits j in relation (2), we obtain

$$E_{\mathrm{tot}}(t) = \sum_j E_j(t) \propto \omega_{\mathrm{ch}}{}^b\ \mathrm{sinc}\left(\frac{\omega_{\mathrm{ch}}{}^b}{2}\, t\right)\sum_j \exp(i\omega_0{}^j t)\,. \tag{3}$$

In our case all bits have the same duration and $\omega_{\mathrm{ch}}{}^b$ is independent of j. $\omega_0{}^j$ is the center frequency of bit j and can be expressed as $\omega_0{}^j = \omega_0 + (\omega_{\mathrm{ch}}/T)T_S(j - 1)$, where ω_0 is the central frequency of the first bit ($\omega_0 = \omega_0{}^1$). Relation (3) becomes particularly simple if the data stream contains the maximum number of bits, i.e., if j runs from 1 to N_b, where N_b is the number of bits in the sequence. The resultant intensity then becomes

$$I(t) \propto \omega_{\mathrm{ch}}{}^{b^2}\mathrm{sinc}^2\left(\frac{\omega_{\mathrm{ch}}{}^b}{2}\, t\right)\frac{\sin^2\left(N_b\,\dfrac{\omega_{\mathrm{ch}}{}^b}{2T_b}\,T_S t\right)}{\sin^2\left(\dfrac{\omega_{\mathrm{ch}}{}^b}{2T_b}\,T_S t\right)}\,. \tag{4}$$

Relation (4) [and in fact essentially the whole treatment starting from relation (2)] is analogous to a much more often discussed experimental case, namely, the far-field intensity pattern that is due to Fraunhofer diffraction by a multislit pattern. Exactly the same equations would result for N_b slits, each with a width $\omega_{\mathrm{ch}}{}^b$ and a slit separation $(\omega_{\mathrm{ch}}{}^b T_S)/T_b$. Time is then replaced by the wave vector perpendicular to the slits, $t \rightarrow k \sin\theta$, where k is the wave number and θ is the diffraction angle.

Figure 2a shows a 10-μs-long pulse chirped over 230 MHz compressed to 22 ns, and the inset shows the echo output on an expanded time scale. The noise in the input pulses is presumably photomultiplier tube shot noise because AOM3 does not open until after the second input pulse. Optimum compression with a 230-MHz chirp would give an echo duration of ~3.8 ns. The current echo signal is a factor of 6 longer. In our experiments the echo duration for large compression factors was often greater than predicted by theory. We believe that this result occurred because the chirp rates for the first and second pulses deviated slightly from the optimum 1:2 ratio. This deviation may be due, for example, to noise and nonlinearity in the voltage ramps sent to the high-voltage amplifier and the electro-optic crystal from the arbitrary function generator. The influence of the 350-kHz laser linewidth was modeled by a random-walk diffusion process, which could not, however, explain the increased echo duration at higher chirp rates.

In the multibit compression case our approach is equivalent to that used in Ref. 5 but differs from the one in Ref. 4 for which all bits could be directly seen in the output signal. In our study we require a Fourier

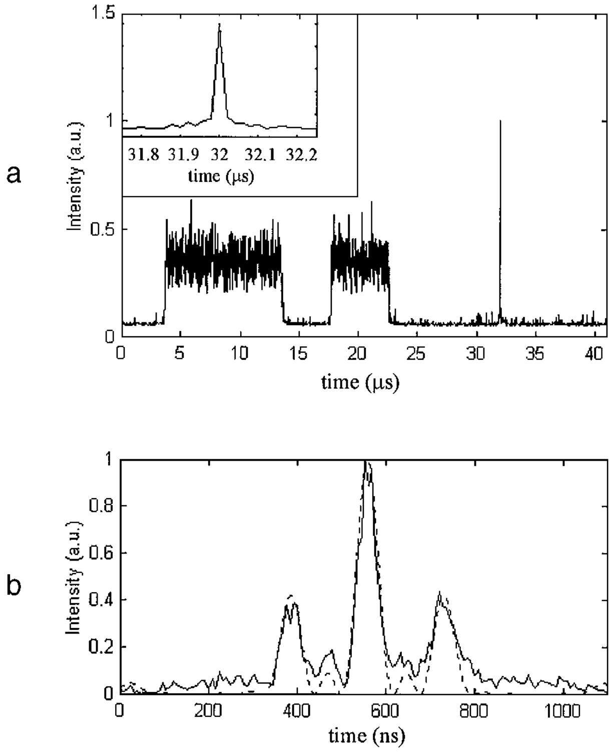

Fig. 2. a, Single-pulse compression of a 10-μs input pulse by a factor of 450 to a full width at half-maximum of 22 ns. Inset, the echo output on an expanded time scale. b, Solid curve, compressed echo output for a 3-bit input sequence; dashed curve, theoretical simulation based on relation (4) (details are given in text).

transform of the output signal for reconstructing the input signal. The multibit experiments included the transformation of a 10-bit sequence by ~2 orders of magnitude from 20 μs to 212 ns. With several bits in the data sequence, low signal strength degraded the sideband structure that contains the information about the bit sequence. The fidelity in the compressed signal thus generally was insufficient for reconstructing the input. With fewer bits the sideband structure can be more easily seen though. The solid curve in Fig. 2b is the echo output from a 3-bit input sequence similar to the 4-bit sequence displayed in Figs. 1c and 1d. Each bit has a duration $T_b = 1$ μs, and these bits are separated by $T_S = 2$ μs. The data are thereby compressed a factor of 14 from 5 μs to 350 ns. The chirp, ω_{ch}, covers roughly 60 MHz during 20 μs. The dashed curve in Fig. 2b is the theoretically calculated photon-echo output with relation (4) used for the input signal in Fig. 1c. Experimental and simulated peak intensities are normalized to unity, and $\omega_{\mathrm{ch}}{}^b$ is used as fitting parameter. As discussed by Graf *et al.*,[5] the shortest duration for a compressed pulse train at a given chirp rate is the same as the duration of a compressed single bit at this given chirp rate.

Although the data in Figs. 2a and 2b demonstrate an order-of-magnitude improvement in single-bit and a factor-of-2 improvement in multibit pulse compression compared with the results of previous investigations,[3,4] a still more interesting experiment would be to compress nanosecond-duration pulses to picosecond duration to reach into the domain that cannot be handled by conventional electro-optic equipment. The present investigation did not include any detailed investigation of the signal levels, but the excitation power was approximately 3–5 mW and the overall pulse duration typically was ~10 μs. The number of echo output photons will be proportional to the product $\sin^2\theta_1 \sin^4\theta_2$ (see, e.g., Ref. 9), where θ_i, the pulse area for pulse i, is given by $\theta_i = 2\,\mu E_i T/\hbar$ and μ is the transition dipole moment. For small pulse areas the number of output photons will essentially be proportional to the quantity $[(\text{electro-magnetic field}) \times (\text{pulse duration}) \times (\text{transition dipole moment})]^6$, which also is proportional to $[(\text{pulse energy}) \times (\text{pulse duration}) \times (\text{transition oscillator strength})]^3$. For a given input pulse energy the number of output photons will consequently be the same for microsecond and nanosecond input pulses if the oscillator strength f is increased by 3 orders of magnitude in the latter case. For nanosecond excitation at highly allowed transitions, $f \approx 0.1-1$, the input power could be kept in the few-milliwatt region and the number of output photons would still be the same as for our microsecond excitation pulses in Tm-doped YAG.

In summary, we have demonstrated photon-echo-based single-bit temporal compression by a factor of 450 and multibit compression by a factor of 14. The single-bit compression represents an order-of-magnitude improvement compared with what had been obtained previously in photon-echo pulse compression. Our current values are limited by the stability of the diode laser and the diode laser control system used in these measurements and by the laser power. There is no reason not to believe that significantly better compression could be obtained with a higher-power and more stable system. We argue that suitable photon-echo materials can be used to compress gigahertz data to terahertz rates and to decompress terahertz data to gigahertz rates, which, e.g., could be an approach to time multiplexing in optical communication.

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