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 107. © 2000 Optical Society of America

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 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 3H4→3H6 transition line of the trivalent rare-earth ion Tm3+ 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 E1 and E2, respectively. The echo output field as a function of time, Ee(t), equals the first input field E1(t) correlated with the second field E2(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 $t_2$. $\omega_0$ 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. $\omega_0'$ is the center frequency for input bit $j$.

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

where $E_1(\omega)$ is the frequency Fourier transform of $E_1(t)$. 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 $\omega_{ch}$ and that $\omega_{ch}T >> 1$. Within the time interval $t \in [t_1 - T_1/2, t_1 + T_1/2]$ we write the electric field of pulse $i$ as $E_i(t) = \exp[-i(\omega_0 + K(t-t_1))(t-t_i)]\exp(-i\mathbf{k}_i \cdot \mathbf{r})$, where $K = \omega_{ch}/(2T_1)$. 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 $\omega_{ch}T >> 1$, the excitation pulses can be regarded as constant in the frequency interval $[\omega_0 - \omega_{ch}/2, \omega_0 + \omega_{ch}/2]$ and zero otherwise. Relation (1) can then be simplified as

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

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 $T_e = 5.5/\omega_{ch}$. If the duration of the first pulse is $T_b$, then $T_e \leq T$ and the chirp rate is kept unchanged, we can still use the result above if we replace $\omega_{ch}$ with $\omega_{ch}b$ [where $\omega_{ch}b = \omega_{ch}(T_b/T)]$. Numerical and analytical calculations show that this result holds as long as $\omega_{ch}T_b >> 1$. 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 $T_b$ to consist of several bits of duration $T_b$ that have their center points separated by a time $T_S$ (Fig. 1c). If only $\omega_{ch}T_b >> 1$, 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 $\omega_{ch}T_b << 1$ and $\omega_{ch}T >> 1$ 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

$$E_{tot}(t) = \sum_j E_j(t) \propto \omega_{ch}b \sin\left(\frac{\omega_{ch}b}{2} t\right) \sum_j \exp(i\omega_0 j t).$$

(3)

In our case all bits have the same duration and $\omega_{ch}b$ is independent of $j$. $\omega_0'$ is the center frequency of bit $j$ and can be expressed as $\omega_0' = \omega_0 + (\omega_{ch}/T)T_S(j - 1)$, where $\omega_0$ is the center frequency of the first bit ($\omega_0 = \omega_0'$. 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

$$I(t) \propto \omega_{ch}b^2 \sin^2\left(\frac{\omega_{ch}b}{2} t\right) \sin^2\left(\frac{\omega_{ch}b}{2T_b} T_St\right).$$

(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 $\omega_{ch}b$ and a slit separation ($\omega_{ch}bT_S)/T_b$. Time is then replaced by the wave vector perpendicular to the slits, $t \rightarrow k \sin \theta$, where $k$ is the wave number and $\theta$ 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
The intensities are normalized to unity, and signal in Fig. 1c. Experimental and simulated peak photon-echo output with relation (4) used for the input dashed curve in Fig. 2b is the theoretically calculated $TS$ are separated by a still more interesting experiment would be to compare the results of previous investigations with 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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References