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Frequency-chirped copropagating multiple-bit stimulated-echo storage and retrieval in Pr^{3+}:$YAlO_3$

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Using a frequency-chirped ring dye laser, we have stored and recalled as much as 48 bits of information with the copropagating stimulated-echo geometry on the $^3H_4$–$^1D_2$ transition in Pr^{3+}:$YAlO_3$. Since the copropagating excitation scheme has all the excitation pulses spatially overlapping, this technique will be useful to the practical implementation of stimulated-echo memory because there is no need for alignment of beams. Our experiments also demonstrate that frequency chirping of the excitation pulses dramatically improves not only pulse-shape reproduction by the echo pulse but also the shot-to-shot stability of the amplitude of the recalled data.

It is well known that the optical stimulated echo can store multiple bits of information in a single electronic state or in a coherent superposition of two states.[1–3] Information storage in the ground electronic state in a solid material at low temperatures is particularly useful because information can be stored for many hours.[4] The backward-stimulated-echo (BSE) scheme,[1–11] in which excitation pulses are counterpropagating or nearly counterpropagating, has an added advantage because it allows spatial and temporal separation of the retrieved data pulses from the excitation pulses and other unwanted echo signals. It is therefore not surprising that most multiple-pulse echo storage and retrieval experiments in solids have involved the BSE scheme.

The implementation of the BSE scheme, however, suffers from two main disadvantages. The first disadvantage arises from the need to overlap and align three excitation laser beams at any given spatial location in the sample. The second disadvantage, which is not unique to the BSE approach, arises from the fact that two different types of laser have to be used for the data stream and the writing and reading pulses. The latter requirement is due to the fact that a multiple-pulse storage scheme usually requires a narrow-band cw source for data pulses, whereas wider-bandwidth pulses are necessary for the write and read pulses.

In this Letter we report a stimulated-echo approach that uses a copropagating geometry to store and retrieve multiple bits in a solid sample, Pr^{3+}:$YAlO_3$. In this approach a single-frequency ring dye laser (RDL) is used as a source for all the input pulses, which copropagate. The copropagating geometry entails no spatial beam overlap nor the use of the phase-matching geometry required in the BSE approach. The desirable echo signal (the faithful replica of the input data pulses) amplitude is a product of the write, read, and data pulse amplitudes. However, the copropagating geometry also allows the echo to arise from the product of two different subpulses of the data pulse stream and the read pulse. In our current research we have circumvented the problem by frequency chirping the read and write excitation pulses. The use of the frequency-chirped pulses was first suggested and demonstrated by storing information in the superposition of degenerate states in Yb vapor by Bai *et al.*[12] We also find that with this new approach the data fidelity and shot-to-shot stability in the retrieved signal are markedly improved compared with the previous approach.

Using the $^3H_4$–$^1D_2$ transition of Pr^{3+}:$YAlO_3$, we have stored as much as 48 bits of information using a chirped RDL. The maximum number of bits that we have stored is limited solely by the electronic circuits that produce the input to the acousto-optic modulator (AOM) and the intracavity phase modulator. The number of stored bits can be increased by improvements in the chirp bandwidth and a faster AOM.

Consider an ensemble of ions in a crystal with a near-degenerate set of ground $|0\rangle$ and excited $|1\rangle$ states that have a central transition frequency ω_0. To store multiple bits of data the sample is excited by two excitation pulses at times t_w and t_d ($t_w < t_d$), where t_w is the write pulse [see Fig. 1(a)]. The data pulse, which begins at time t_d, is a complex pulse consisting of many short subpulses, which represent data. The informa-

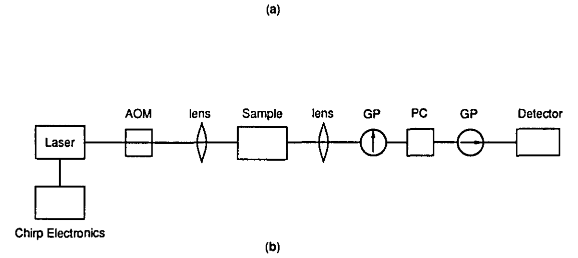

Fig. 1. (a) Temporal position of the write, data, read, and echo pulses for the copropagating stimulated-echo scheme. (b) Schematic of the experimental setup. GP, Glan prism polarizers; PC, Pockels cell.

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tion is stored as a population modulation in the ground and excited electronic states as a function of the absorption frequency within the inhomogenously broadened line. To recall the data the sample is excited by a single read excitation pulse at time t_r, which results in a coherent emission (echo) beginning at time $t = t_r + (t_d - t_w)$.

For a practical multiple-bit stimulated-echo memory, the data pulses need to be produced from a cw laser because it provides the greatest flexibility in producing complex and arbitrary optical data pulses. In the small-angle limit of all input pulses, the echo electric-field amplitude $E_e(t)$ is a temporal Fourier correlation/convolution of the write, data, and read pulses and can be expressed as[12]

$$E_e(t) \propto \int_{-\infty}^{\infty} E_w^*(\omega)E_d(\omega)E_r(\omega)\exp(i\omega t)\mathrm{d}\omega, \tag{1}$$

where E_w, E_d, and E_r are the Fourier transforms of the write, data, and read pulses, respectively. If the bandwidths of the read and write pulses are uniform over the frequency range of the data pulses, then $E_w(\omega)$ and $E_r(\omega)$ can be removed from the integral in relation (1) and $E_e(t)$ is proportional to $E_d(t)$.

In addition to the requirements outlined above, the optimum echo size is obtained if the pulse areas of the read and write pulses are $\sim\pi/2$.[5,13] Therefore, if the RDL is used to provide the read and write pulses, these pulses must be temporally long to get a $\pi/2$ pulse area. Unfortunately, because the long write and read pulses have small frequency bandwidths, they are unable to cover the much larger bandwidth of the data pulse stream. In our previous research we circumvented this problem by using the output of the pulsed dye laser to produce the write and read pulses.[13]

We have attempted to address all the drawbacks of this previous approach by using the RDL to produce the write and read pulses, thereby eliminating the pulsed dye laser, and by frequency chirping the RDL during the write and read pulses to frequency broaden the output. The frequency chirping has led to a breakthrough by allowing the input sequence and the echo pulses to be copropagating with no beam alignment problems.

The RDL (Coherent Radiation Model CR 699-21), with an intrinsic bandwidth of 1 MHz, is chirped by inserting a 5 mm × 10 mm cross section and 66-mm-long AD*P crystal (Inrad) in the laser cavity in a manner similar to that described in Ref. 14. The electrical pulse is applied across the sides, which are separated by 5 mm. The drive electronics for the frequency chirp are the same as in Fig. 2 of Ref. 14. When an electric pulse is applied to an electro-optic crystal such as AD*P, its refractive index changes in proportion to the electric field. The change in (transverse) refractive index changes the optical length of the ring cavity, causing the laser to shift its frequency. The shifted frequency ν is given by

$$\nu = \nu_0(1 - F\xi l/L), \tag{2}$$

where ν_0 is the unshifted frequency, F is the electric field applied to the crystal, ξ is a constant proportional to the crystal electro-optic coefficient, l is the crystal length, and L is the unshifted optical length of the RDL cavity.

The experiment to store multiple data pulses was performed on the ${}^3H_4$–${}^1D_2$ transition in Pr^{3+}:$\mathrm{YAlO_3}$ ($\lambda = 610.5$ nm). The 0.4-mm-long crystal with $\sim$75% absorption at the line center was immersed in the liquid-helium cryostat. The pressure in the cryostat was 1.3 atm, and the temperature approximately 4.6 K. At these conditions the liquid helium slowly evaporates. The experimental setup shown in Fig. 1(b) is simple, requiring only chirp electronics, an AOM, and a Pockels cell between crossed polarizers for suppressing the excitation pulses before they reach the photomultiplier tube (RCA C31034). The top trace in Fig. 2 shows the temporal position of the input pulses and the echo output. The first excitation on the left of the top trace is the 1.6-μs-long write pulse with an energy of $\sim$30 nJ. When the write pulse is on, the voltage on the AD*P crystal is swept from 450 to 0 V, and a frequency chirp of $\sim$75 MHz is produced. A similar sweep occurs during the read pulse. The second pulse from the left in the top trace of Fig. 2 is actually a train of the data pulses, each of which is 25 ns wide. The data train starts at $t_d = 4$ μs after the write pulse ($t_w = 0$). When the data pulse train is on, the AD*P crystal voltage is held near 225 V, so that the

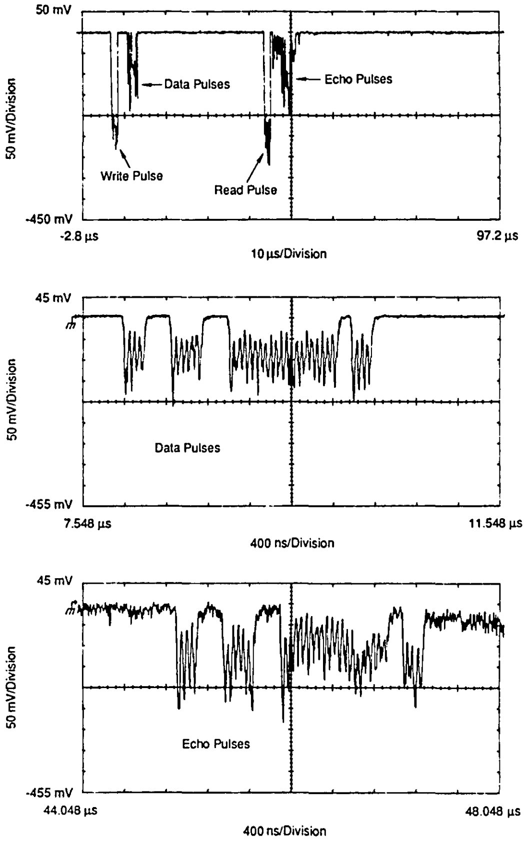

Fig. 2. Temporal position and the intensities of the input and echo pulses. The top trace, monitored with a photomultiplier tube, shows the temporal position of all the excitation pulses and the echo pulse. The middle trace is recorded with a photodiode and shows the input data pulse sequence on an expanded scale. The bottom trace shows the echo pulses on an expanded time scale.

laser frequency is at the center of the chirp produced during the write and read pulses.

An expanded trace of the data pulse train, monitored with a photodiode, is shown in the middle trace of Fig. 2. As is evident from this trace, the data pulse train contains a series of ones and zeros, with the total number of bits being equal to 48. The 1.5-μs-long read pulse, with an energy of $\sim$25 nJ, is the third pulse from the left in the top trace of Fig. 2. This last pulse in the top trace in Fig. 2 is the echo pulse. The bottom trace in Fig. 2 shows the expanded view of the echo pulse. Note that the traces in Fig. 2 are from a single shot and are not time averaged. The Pockels cell between crossed polarizers in front of the detector suppresses the read, write, and data input pulses by a factor of $\sim 10^3$ compared with the output data sequence. In comparing the input data train shown in the middle trace of Fig. 2 and the echo output shown in the bottom trace of Fig. 2, we see that the pulse-shape reproduction is good, even though the chirp is not linear during the read and write pulses, and there is some residual chirp (5–10 MHz) during the data pulses owing to imperfect electronic circuits producing the high voltage ramps. In the top trace of Fig. 2, the signal between the read pulse and echo is due to the leakage from the trailing edge of read pulse, when the Pockels cell is turned on.

Another interesting aspect of the echo pulse shown in Fig. 2 is that, when the chirping in the laser is turned off during either the read or the write pulse, the echo pulse becomes structureless, thereby proving that chirping is essential to reproduce input pulse shapes when a single-frequency laser is used. The shot-to-shot stability of both the shape and the amplitude of the echo pulses is excellent. Our experiments demonstrate the production of only the echo signal that corresponds to the product of the write, data, and echo pulses. Other unwanted signals are missing owing to the unique frequency labeling by the frequency chirp. For instance, we do not see any signal arising from interference between the leading and trailing pulses in the data sequence and the read pulse. These unwanted signals would appear along with the retrieved data signal if frequency chirping were not used.

When one or more data pulses are omitted by removing the electrical signal to the AOM, the intensities of the remaining echo pulses are virtually unchanged. This observation implies that there is little cross talk between the data pulses. The implication of the negligible cross-talk result is that many more data pulses than we stored can be stored at one location, without any diminution of the signal-to-noise ratio.

In conclusion, we have observed a new approach to multiple-pulse stimulated-echo storage using a copropagating geometry in conjunction with a frequency-chirped laser. Our approach offers ease of operation because it requires no alignment of beams. In addition, our experiments demonstrate that the echo not only reproduces the input pulse shape but also has high shot-to-shot amplitude stability.

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