Photon-echo-based logical processing

Kröll, Stefan; Elman, U.

Published in:
Optics Letters

1993

Citation for published version (APA):
Kröll, S., & Elman, U. (1993). Photon-echo-based logical processing. *Optics Letters*, *18*(21), 1834-1836. http://www.opticsinfobase.org/abstract.cfm?URI=ol-18-21-1834

Total number of authors:
2

Photon-echo-based logical processing

S. Kröll and U. Elman

Department of Physics, Lund Institute of Technology, Box 118, S-221 00 Lund, Sweden

Received June 4, 1993

Word-by-word logical AND and OR operation with photon-echo processing is demonstrated for what is to our knowledge the first time. The photon-echo process can store sequences of optical data before processing. The present logical operations on 8- and 4-bit words are performed by using single-shot frequency-chirped photon echoes. Data rates of approximately 1 MHz, input energies of 1–10 nJ/bit, and output energies in the picojoule-per-bit range are demonstrated by using a transition with a transition probability of only 20 s^{-1}.

Several papers (e.g., Refs. 1–8) that demonstrate various aspects of optical data storage and processing through the use of photon echoes have recently appeared. Together with persistent spectral hole-burning (e.g., Refs. 9–11), the photon-echo approach has the particular feature of being able to store optically a large number of bits ($>10^3$) in one diffraction-limited spot. This is done by use of different frequency components within an inhomogeneously broadened absorption line for storing and addressing data in addition to the use of two dimensions in space. In persistent spectral hole burning one addresses different spectral intervals within the absorption line by explicitly changing the frequency of the writing and reading laser between each bit. The photon-echo approach is in some respects more subtle, and one addresses different spectral intervals here by storing the frequency-domain Fourier transform of the time-domain input signal.[12] In this Letter we demonstrate what are to our knowledge the first word-by-word logical AND and OR operations that use photon echoes. The two-pulse photon echo is utilized.[13] For two excitation pulses separated a time T a new output pulse is generated a time T after the second pulse, provided that the two pulses have interacted with the same atoms and that the inhomogeneous dephasing time of the transition $< T <$ the homogeneous dephasing time. We select the logical operation by explicitly changing the frequency of the input data laser beam during the input data stream and in this way determining which pulses interact with which frequency interval.

The experimental setup is shown in Fig. 1. The output from an argon-ion-laser-pumped ring dye laser is modulated by two acousto-optic modulators, a Soro-MAR-50 (AOM1) and an Isomet 1205C-2 transducer with a D322 driver (AOM2). The acoustic rf frequency in the Isomet modulator can be changed with a rate of 10 MHz/μs. The pulse train is focused into a Pr-doped YAlO$_3$ crystal (XTAL; Pr^{3+} concentration 0.1%, optical density 1.3) immersed in a liquid-helium bath cryostat (Cryovac Model 100). The recollimated output pulses are directed through another Isomet modulator (AOM3), which suppresses the excitation pulses and directs the output signal to a photomultiplier tube (PMT). The photomultiplier signal is registered by a Tektronix 2431L 300-MHz storage oscilloscope and subsequently transferred to a personal computer.

The key concept behind the word-by-word logical operations performed here is illustrated in Fig. 2. Only when two pulses interact with the same frequency group within the inhomogeneously broadened line is a photon echo generated, i.e., both pulses must excite the same atoms. This is the reason that only the pulse pair p and q and not the pair p and r produces an echo output pulse in trace a. The OR operation is actually two AND operations, for which the outputs of these two operations occur at exactly the same time. Again two pulses generate an echo when, and only when, they both address the same frequency interval. The complete operation in trace c is (bit u AND bit v) OR (bit p AND bit q). If both bit v and bit q are high, bit u OR bit p is the operation effectively performed. The output from the OR operation is not binary. If both bits, u and p, are high, the output is twice as large as if only one of them is high. Because u and p correspond to light pulses with slightly different frequencies, the output signal strength is proportional to the number of contributing bits. This is in contrast to photon echoes that use mixed binary representations in which the output is proportional to the square of the number of contributing bits.[5,7]

Experimental data for which the AND operation and the OR operation have been implemented according to the concept described above and generalized to sequences of data (words) instead of single pulses are shown in Figs. 3 and 4, respectively. Trace a in Fig. 3 shows an AND operation on the two 8-bit words 01010101 and 10101010. The corresponding output is zero. Trace b shows an AND operation on the two 8-bit words 01010101 and 01010101. The

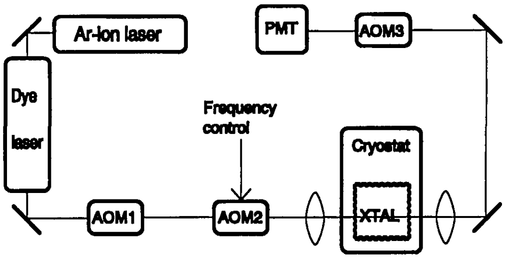

Fig. 1. Experimental setup.

0146-9592/93/211834-03$6.00/0

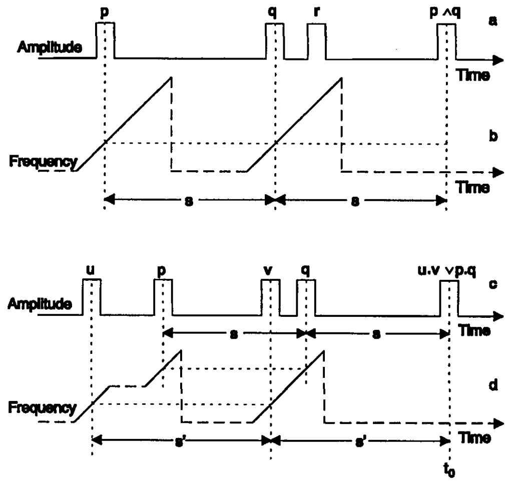

Fig. 2. Conceptual picture to explain the approach used for the AND and OR operations. Traces a and b illustrate the principle of the AND operation, and traces c and d describe the OR operation. Traces a and c show the input and output pulse sequences, and, below each of these two traces, traces b and d show how the laser frequency is changed during the corresponding input sequences. Any time a specific frequency interval has been addressed twice a two-pulse photon echo is produced. In trace a an AND operation on bit p and bit q is shown. These two bits address the same frequency interval, while bit r is transmitted at some other frequency. Bit p and bit q are separated a time interval s; thus the photon-echo output occurs a time interval s after bit q. In trace c an OR operation on bit u and bit p is performed. Bit u and bit v address the same frequency interval, producing an output at time t_0. Further, bit p addresses the same frequency interval as bit q. These two pulses also produce an output at time t_0. Thus, with pulses v and q present, there will be an output signal at time t_0 as long as at least one of the pulses u and p is present.

output is the word 01010101. Trace c shows the shift in light frequency after AOM2 versus time. All traces are single-shot traces as recorded by the photomultiplier. Each input data bit has a duration, τ (FWHM), of $\tau = 1$ μs, and the input data bit energy was measured to be approximately 5–10 nJ. Considering the measured suppression ratio of AOM3 to be 2000, we estimate the output pulse energy to be a few picojoules. As output pulses are shown on the same oscilloscope trace and the input pulse energies are measured at the cryostat entrance, the output pulse intensity is essentially obtained simply by comparing its size with the size of the input pulses and dividing by the factor 2000. Values given are those extrapolated to the crystal surface. Several loss mechanisms then occur as the pulse travels from the cryostat to the photomultiplier, but losses after the crystal are strongly dependent on the individual optical configuration chosen, and the values at the crystal therefore seem to be the ones that are most relevant. The frequency bandwidth of the input data pulses is approximately $4/\tau$ (FWHM of a square pulse of duration τ). To certify that the laser indeed addresses different frequency parts for the different bits requires that the frequency chirping rate, R, be at least $(4/\tau)/\tau = 4/\tau^2$. Thus in the present case $R > 4$ MHz/μs. The actual value used in Fig. 3 is 4.2 MHz/μs. Chirping rates below the calculated limit resulted in incorrect results in the logical operations, such as nonzero outputs when

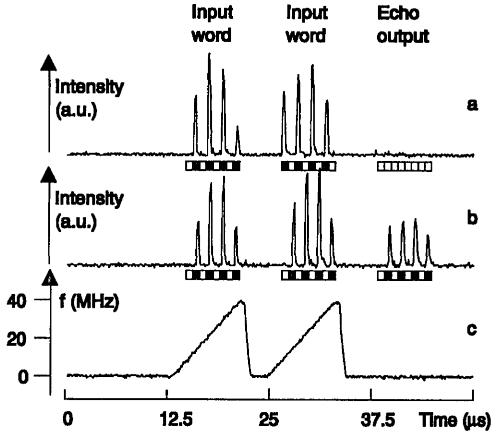

Fig. 3. Experimental curves demonstrating photon-echo AND operation. Traces a and b both show two input 8-bit words and the corresponding photon-echo output, all recorded by the photomultiplier. The 8-bit words are also marked below each trace, where a filled square denotes a high bit. The operation in trace a gives zero output, as it should. Trace c shows the laser frequency as the data bits are transmitted. The data input pulse energies are a few nanojoules, and the output pulse energy is a few picojoules.

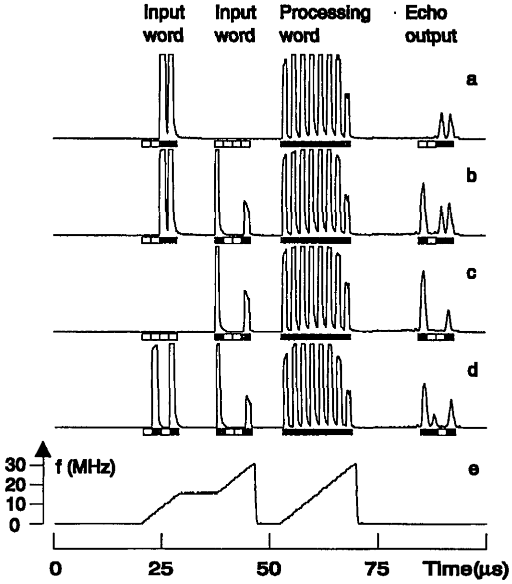

Fig. 4. Experimental curves demonstrating photon-echo OR operation. Traces a–d show OR operations on different pairs of 4-bit input words. The 4-bit words are also marked below each trace, where a filled square denotes a high bit. Trace e shows the laser frequency as the data bits are transmitted. The groups of 8 bits between the input words and the output are processing pulses. Any of the processing pulses will act as the second pulse in a two-pulse photon echo and thus produce an echo if the corresponding absorption frequency had been excited by a bit in any of the two input words. A processing pulse at a frequency not addressed by any of the input data bits will have no effect on the output. The input pulse energies are in the 1–10-nJ range, and the output pulse energies are near 1 pJ.

the output should be a zero. Unless the transition is saturated, faster sweeps yield lower output signals. This was experimentally observed as well as verified by theoretical simulations.[14]

In Fig. 4 the bottom trace (trace e) again shows the change in light frequency after AOM2. The maximum frequency chirp of AOM2 is 45 MHz. However, the diffraction efficiency as a function of frequency changed significantly. This caused the intensity of the different bits to depend on the frequency of the rf signal to AOM2. This can be overcome, at least to a certain extent, by use of an AOM with higher carrier frequency or of several AOM's in tandem. For the OR operation the temporal separation between the rising edge of two consecutive bits was chosen to be twice the bit duration. Thus the OR operation required a frequency chirp rate of $R = (4/\tau)/(2\tau) = 2/\tau^2$. The bit duration $\tau = 1.3$ μs gives a required chirp rate of 1.2 MHz/μs. The actual chirp rate in Fig. 4 is 1.5 MHz/μs. Traces a–d demonstrate different combinations of input words with their respective outputs. For a high-output bit the pulse energy is near 1 pJ. As in Fig. 3, the high-output bits are clearly seen, while the signals from the low-output bits do not rise above the background noise level. Consequently there are no problems with thresholding. The time separations between input and output data pulses are longer for the OR operation in Fig. 4 than for the AND operation in Fig. 3. The reason for this is that a data-processing sequence, the third group of input pulses in the traces in Fig. 4, is needed for performance of the OR operation. The longer time separation between input and output pulses causes the output signal for the OR case to be slightly smaller than in the AND case as a result of homogeneous dephasing.[15]

Except for losses in imperfect optics, etc., which are not analyzed in detail in this Letter, there are two mechanisms that determine the strength of the output signal at given input pulse intensity: the efficiency of the photon-echo process itself and the homogeneous dephasing time. The contribution that is due to homogeneous dephasing is readily estimated. With an excitation energy of 5–10 nJ/bit, the total excitation energy E will be in the 50–100-nJ range. For these energies the homogeneous dephasing time $T_2(E)$ is $\sim$20 μs.[16] Thus the output signal in Fig. 3 is attenuated by approximately a factor of $\exp[4 \times 12/T_2(E)] \approx 10$ as a result of homogeneous dephasing. The efficiency in the photon-echo process itself, neglecting relaxation, consequently is 0.1–1% in the present case.

The concept presented in this Letter may be particularly attractive when we are aiming for higher data rates (>100 MHz), because then diode lasers, which easily can be frequency chirped over long intervals and modulated at high rates, can be used for the excitation. To obtain higher speed and/or lower pulse energies, one should use transitions with higher transition probabilities. The transition probability for the transition used here is only $\sim$20 s^{-1}.[15] Unfortunately, higher transition probabilities will also mean shorter homogeneous dephasing times. However, for the crystal transitions currently being tested in photon-echo storage and processing, the homogeneous dephasing time is far from being limited by the transition probability. Hence new materials may lead to considerably lower energy requirements and/or higher speed. A final important point is that certain logical operations, such as NOT, require that the phase of the input pulses be controlled,[17] which was, however, not possible with the present setup.

Convolution and correlation operations that use photon echoes have been performed several times (e.g., Refs. 6 and 18). Binary multiplication with photon echoes has been demonstrated.[5,7] The present research on word-by-word logical operations with photon echoes further demonstrates the ability of coherent transient processes to carry out operations optically that today are performed with electronic computers.

The continual support of S. Svanberg and M. Aldén is gratefully acknowledged. The Pr:$YAlO_3$ crystal was provided by R. Kachru of SRI International, Menlo Park, California. This work was supported by the Swedish Natural Science Research Council and the Crafoord Foundation.

References

1. M. Mitsunaga, R. Yano, and N. Uesugi, Opt. Lett. **16,** 1890 (1991).
2. S. Kröll, L. E. Jusinski, and R. Kachru, Opt. Lett. **16,** 517 (1991).
3. S. Saikan, T. Kishida, A. Imaoka, K. Uchikawa, A. Furusawa, and H. Oosawa, Opt. Lett. **14,** 841 (1989).
4. A. Rebane and R. Kaarli, Chem. Phys. Lett. **101,** 317 (1983).
5. W. R. Babbitt and T. W. Mossberg, Appl. Opt. **25,** 962 (1986).
6. X. A. Shen and R. Kachru, Opt. Lett. **17,** 520 (1992).
7. D. Manganaris, P. Talagala, and M. K. Kim, Appl. Opt. **31,** 2426 (1992).
8. X. A. Shen, Y. S. Bai, and R. Kachru, Opt. Lett. **17,** 1079 (1992).
9. W. E. Moerner, W. Lenth, and G. C. Bjorklund, in *Persistent Spectral Hole-Burning: Science and Applications,* W. E. Moerner, ed. (Springer-Verlag, New York, 1988), p. 251.
10. U. P. Wild, C. De Caro, S. Bernet, M. Traber, and A. Renn, J. Lumin. **48/49,** 335 (1991).
11. F. M. Schellenberg, W. Lenth, and G. C. Bjorklund, Appl. Opt. **25,** 3207 (1986).
12. T. W. Mossberg, Opt. Lett. **7,** 77 (1982).
13. I. D. Abella, A. Kurnit, and S. R. Hartmann, Phys. Rev. **141,** 391 (1966).
14. U. Elman, Diploma thesis, Lund Reports on Atomic Physics, LRAP-136 (Lund Institute of Technology, Lund, Sweden, 1992).
15. R. M. Macfarlane and R. M. Shelby, in *Spectroscopy of Solids Containing Rare Earth Ions,* A. A. Kaplyanskii and R. M. Macfarlane, eds. (Elsevier, New York, 1987), p. 51.
16. S. Kröll, E. Y. Xu, and R. Kachru, Phys. Rev. B **44,** 30 (1991).
17. N. N. Akhmediev, Opt. Lett. **15,** 1035 (1990).
18. Y. S. Bai, W. R. Babbitt, N. W. Carlson, and T. W. Mossberg, Appl. Phys. Lett. **45,** 714 (1984).