Demonstration of optical coherent transient true-time delay at 4 Gbits/s

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Multigigabit-per-second true time delay (TTD) was experimentally demonstrated by use of optical coherent transient techniques in a Tm^{3+}:YAG crystal. A delay accuracy of 1 ps and a delay resolution of 7 ps (both measurement limited) were achieved. The retrieved data retained good fidelity. © 2001 Optical Society of America

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Phased-array antennas (PAAs) provide many advantages compared with mechanically steered dishes to benefit high-performance radar systems, including beam steering without physical movement, fast scanning across the sky in two dimensions, precise elemental amplitude and phase control to reduce and direct the spatial sidelobes, and less power consumption and weight.[1] A PAA combines the signals from as many as thousands of radiating elements of an antenna array to direct the beam at a certain angle in space. The sidelobe and the direction are determined by control of the phase shifts and amplitude weights of the signal across the array. Phase-shifting devices have succeeded in beam steering PAAs for fractional bandwidths of 2% or less. However, they have not worked for microwave antennas at large fractional bandwidths because of the inherent beam squint problem at large steering angles from the antenna's boresight.[1–3]

Future general-purpose PAAs are expected to perform over a broad band (a few hundred megahertz to 20 GHz) with fractional bandwidths of nearly 100% because of the integration of radar and communication functions onto a common antenna. True-time-delay (TTD) techniques are an attractive way to realize broadband operation. Instead of phase shifts, time delays are introduced to the signal of each element to facilitate more-efficient elemental vector summation and distribution independent of frequency. The electronically controlled switched coaxial cable TTD networks that are currently used in radar systems are heavy and bulky and typically operate on the subarray level. Optically controlled TTD has the advantages of parallelism, immunity from electromagnetic interference, compactness, and light weight.[2] Several schemes for achieving broadband operation, such as switched optical fiber delay line networks,[4,5] dispersive fiber delay lines,[6] Bragg grating fiber delay lines,[7] and spatial light modulator–based free-space phase-compensated systems,[8] have been proposed and demonstrated in the past two decades. All these involve parallel switching of the rf signals carried by light through variable optical path lengths to produce the desired delays. The complexity of network switching and large hardware requirements mean that these systems can achieve only a limited number of bits of temporal resolution, making full array processing impractical.

Optical coherent transient (OCT) techniques have been proposed as a possible way to achieve broadband high-resolution TTD.[9] OCT technology, also known as spatial–spectral holography, offers a unique way to use the space and frequency dimensions of inhomogeneously broadened absorbers to handle thousands of high-resolution delays in a compact volume of a crystal. TTD is achieved through a stimulated photon echo process. A delay is preprogrammed in the medium as a spectral grating by two temporally separated pulses that interfere coherently. When an optical carrier with a rf signal passes through the medium, the output (or stimulated photon echo) is essentially a delayed replica of the input. The time delay on the signal equals the time interval between the two programming pulses. Theoretically, one can use the same spatial volume to contain thousands of delays in the form of spatial–spectral gratings with various periods. The programming process can be a single-shot event[9] or an accumulation of single shots,[10] and the programming pulses can be brief, chirped,[11] or temporally patterned.[12] The delayed signals on the output can be spatially separated from the transmitted inputs by an angled beam or a box phase-matching geometry such that they can be read out continuously without interference from the inputs. OCT technology provides a highly parallel, compact TTD device. Crystals doped with rare-earth ions (such as Er^{3+}:$LiNbO_3$ and Tm^{3+}:YAG) offer delays of as much as several microseconds on signals that have several tens of gigahertz bandwidth with projected time–bandwidth products of 10^4 or higher. Experiments with Tm^{3+}:YAG at a narrow bandwidth (~40 MHz) demonstrated delays of more than 1 μs with a resolution of 75 ps.[11]

In this Letter we report our recent experimental demonstration of an OCT TTD on a bandwidth of more than 3 GHz. We used a 5.5-mm-long YAG crystal doped with Tm (0.1 at.%) cooled to liquid-helium temperature as the sample medium. Programming was done with brief pulse pairs at 793 nm with an accumulation scheme in which the same programming pulse pair is repeated many times within the grating's lifetime (~10 ms) such that the grating can be built up to and maintained at high strength with low programming power.

Figure 1 shows a schematic of the setup. A Ti:sapphire laser with a regenerative amplifier and an external etalon provided 30-ps Fourier-transform-limited pulses at a 1-kHz repetition rate. Beam splitters BS1 and BS2 divided the beam into beams 1, 2, and 3 at a power ratio of 2/1/2 within 10%. An adjustable delay line made the separation between the programming pulses on beams 2 and 1 nominally 9.7 ns. The beams were focused to a spot of 100 μm ($1/e$ radius) and overlapped in the crystal with an angle of less than 1/50 rad. Each programming pulse carried approximately 8 μJ of energy. The medium was exposed to the programming pulse pairs, controlled by an accousto-optical modulator (AOM1), for 50 ms (equal to 50 shots). During this time the spectral grating could be accumulated to its maximum strength.[10] The signal to be delayed was a 6-bit binary sequence (1 0 1 1 0 1) made from a train of 30-ps laser pulses at a data rate of 4 Gbits/s to mimic an optical carrier and rf signals. It was created by a multipath delay line [Fig. 1(b)] on beam 3. The energy of the four pulses that represent the 1's was 1.3, 1.0, 1.0, and 0.7 μJ, respectively. Figure 2 shows the input sequence on the upper trace. The power nonuniformity of the 1's was due to the energy losses on the optical surfaces in the multipath delay line. The input pulse train was sent into the crystal along the Beam 1 path 1.0 ms after the last programming pulse. The delayed coherent transient response signal generated in the crystal was detected in the direction of transmitted Beam 2 with a 12-GHz photodetector and recorded with a 3-GHz oscilloscope. The AOMs and the chopper were synchronized to the subharmonics of the laser shot at 1/64 kHz. The double wheel chopper could be set to an arbitrary duty cycle. The programming–processing operated in cycle with a period of 64 ms. During each period, AOM1 was opened first for 50 ms for programming pulses while AOM2 and the chopper were closed. AOM2 was used to protect the detector from the strong programming pulses on Beam 2. Then the chopper let the data sequence through the crystal while AOM2 opened the detector to the output for 14 ms. The lower trace in Fig. 2 shows the delayed output (echoes with ~0.1% efficiency). Because programming pulse 1 and input data sequence 3 marked with arrows on the lower trace were spatially separated from the echoes, they were seen only as scattered light. Programming pulse 2, in the same direction as the echo, was observed because of the leakage from AOM1. The AOM1 and AOM2 could not be switched off and on alternately immediately between pulse 2 and the echo to block leakage because of the slow response times (1 μs and 25 ns for AOM1 and AOM2, respectively). From the scattering and leakage we can get the timing of the pulses in one shot, so the delay can be measured directly. The output signal was delayed by 9.7 ns with respect to the input signal, which was the amount of delay set by the programming pulses. The output shows good fidelity up to the 3-GHz bandwidth limit of our oscilloscope. The programming pulses (with approximately 30-GHz bandwidth) programmed the whole bandwidth of 17 GHz of the medium. The data sequence had a spectrum of 30 GHz at a bit rate of 4 Gbits/s. The delayed output is expected to have a bandwidth of 17 GHz at the same bit rate as the input. The multipath delay line could have generated a data sequence at bit rates up to 10 Gbits/s, but in our experiment the measurement limit on the bandwidth was set by the oscilloscope to 3 GHz. Thus the data rate achieved was measurement limited.

To demonstrate the accuracy and resolution of the delay, we tuned the timing of the programming pulse pair by varying the free-space path difference of the

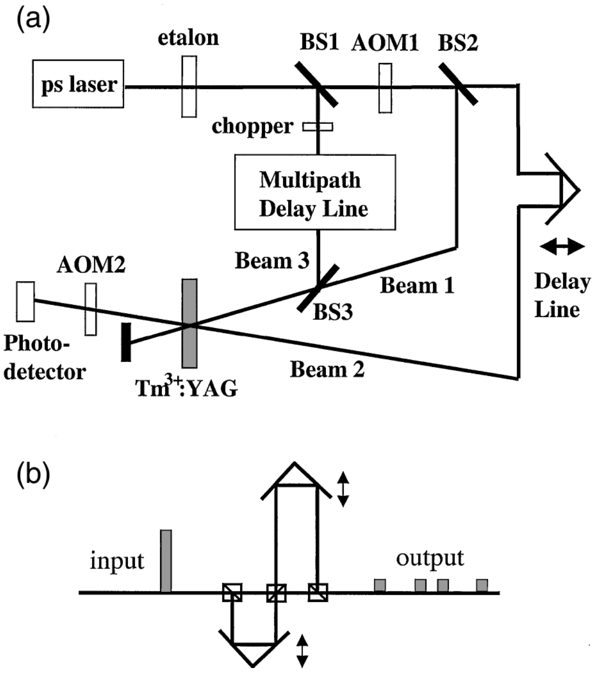

Fig. 1. (a) Schematic of the experimental setup. (b) Multipath delay line for generation of input data sequence.

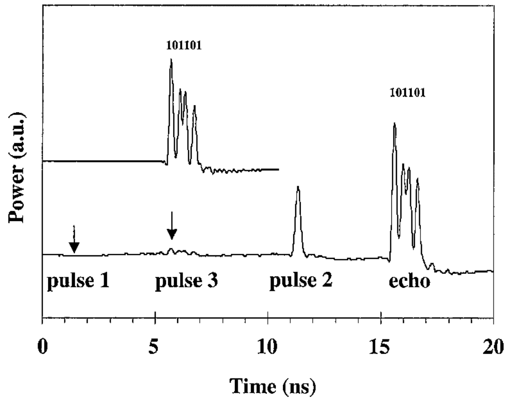

Fig. 2. Upper trace, 1 0 1 1 0 1 input data sequence at 4 Gbits/s. Lower trace, output of the delayed data sequence (echo) from the crystal, including scattered light from Beam 1, input data (pulse 3), and the leakage of Beam 2 from AOM1. All curves were averaged over 50 shots measured with a 12-GHz photodetector and recorded with a 3-GHz oscilloscope.

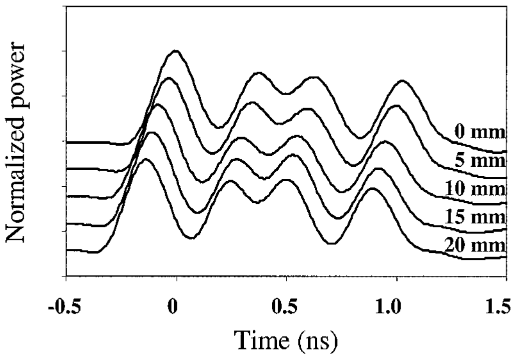

Fig. 3. Delayed data sequence averaged over 50 single shots and normalized at various lengths of delay line with respect to the nominal position at 2.91 m (9.7 ns).

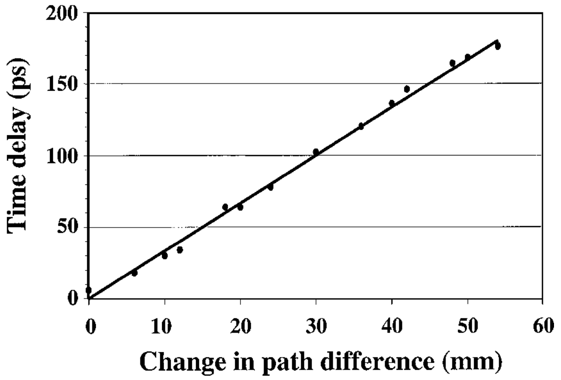

Fig. 4. Measured delays (filled circles) and expected delays (solid line) versus introduced path differences.

pair with a micrometer in the delay line. The length was varied over 54 mm in one direction from the nominal position. The delay accuracy at each point was measured by use of the average of 50 single-shot captures of the output signal. Figure 3 shows the output at various delays with respect to the nominal case, with the first bit centered at 0 ns. The amplitudes of the signals are normalized. Power fluctuation of less than 30% was observed owing to fluctuations in the laser power along the course of the experiment and to changes of overlap in programing beams when the delay line was adjusted to different positions. Figure 4 gives the measured delays (filled circles) relative to the introduced path differences. The fine-tuned delays were measured with a computer program that calculated the time shifts of the signal traces at various positions with respect to the trace at a nominal position by a least-rms fit. The predicted delay is plotted as a solid line. The standard deviation of the difference between the measured and the calculated delays was 1 ps. To determine the delay jitter in a single-shot output, we measured the delays of 50 single-shot outputs at one position (30 mm). A delay jitter of 7 ps rms was obtained. The timing jitter of the input sequence was also measured with 50 signal shots to be 7 ps rms. Thus the delay jitter is measurement limited. The measurement accuracy of 1 ps (determined from the average of 50 shots) is thus limited by the same timing jitter.

This demonstration has shown that one can perform TTDs on multigigahertz-bandwidth signals by using OCT techniques. The delayed output retains good signal fidelity, with excellent delay accuracy and resolution. The bandwidth was limited to 3 GHz by the oscilloscope in the experiment. The medium permits processing of bandwidths that exceed 10 GHz. Although the delay used in programming for the demonstration was created with a free-space delay line and was regenerated by the crystal, OCT TTD programming does not necessarily rely on temporally separated pulses. Instead, a frequency-chirped laser could be used to program delays by offsetting frequencies at a given chirp rate.[11,12] Chirped diode lasers will make the practical device more compact, lighter, and more power efficient. Alternatively, programmed delays can be built up from correlations of the incoming signals and a reference beam, which make the OCT TTD well suited to performing adaptive beam forming and jammer nulling.[13] A single crystal could process several thousand delays in parallel and directly control all the elements of a large phased-array antenna at high data rates with large fractional bandwidth.

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References

1. E. Brookner, Sci. Am. **252,** 94 (1985).
2. H. Zmuda and E. N. Toughlian, *Photonic Aspects of Modern Radar* (Artech House, Boston, Mass., 1994).
3. S. Sabatini and M. Tarantino, *Multifunction Array Radar* (Artech House, Boston, Mass., 1994).
4. R. A. Soref, Appl. Opt. **23,** 3736 (1984).
5. W. Ng, A. A. Walston, G. L. Tangonan, J. J. Lee, I. L. Newberg, and N. Bernstein, J. Lightwave Technol. **9,** 1124 (1991).
6. R. Soref, Appl. Opt. **31,** 7395 (1992).
7. M. Wickman, L. Dozal, L. J. Lembo, and J. C. Brook, Proc. SPIE **2560,** 148 (1995).
8. E. N. Toughlian and H. Zmuda, J. Lightwave Technol. **8,** 1824 (1990).
9. K. D. Merkel and W. R. Babbitt, Opt. Lett. **21,** 1102 (1996).
10. M. Tian, J. Zhao, Z. Cole, R. Reibel, and W. R. Babbitt, J. Opt. Soc. Am. B **18,** 673 (2001).
11. K. D. Merkel and W. R. Babbitt, Opt. Lett. **23,** 528 (1998).
12. K. D. Merkel, Z. Cole, and W. R. Babbitt, J. Lumin. **86,** 375 (2000).
13. R. T. Weverka, K. Wagner, and A. Sarto, Appl. Opt. **35,** 1344 (1996).