An Ultrafast Variable Optical Delay Technique

K. L. Hall, *Senior Member, IEEE*, D. T. Moriarty, H. Hakimi, F. Hakimi, B. S. Robinson, and K. A. Rauschenbach, *Member, IEEE*

***Abstract*—We demonstrate a novel method capable of achieving ultrafast variable delay. This technique utilizes temporal gratings to vary the timing of optical pulses. Ultrafast, variable optical delays may be used in optical clock recovery circuits, all-optical phase-locked loops, and other applications.**

***Index Terms*—Clock recovery, optical communications, optical data processing, optical delay, optical fiber dispersion, synchronization.**

I. Introduction

THE ABILITY to vary the arrival time or phase of optical signals is a crucial function in many optical and electrooptical systems. For example, in high-speed optical transmission systems, local clocks must be synchronized to incoming data streams. Similarly, applications of optics to microwave systems such as antenna remoting and phased-array radar require accurate and variable time delays. In these types of systems it may be acceptable to use slow techniques for achieving variable optical time delays. In the case of packet-switched networks however, where the timing of the data payload within a packet is variable, clock synchronization or lockup may need to be quite fast. Any high-speed processor employing optical logic will also require high-speed synchronization. To date, a number of relatively slow variable optical delay schemes have been demonstrated. For example, the timing of an optical pattern may be altered by stretching an optical fiber or an air gap in the optical path [1] or by tuning a source wavelength at the input to a dispersive path [2]. Alternately, electrooptic phase-locked loops may be used [3]–[5]. However, all of these techniques are too slow for packet-switched network and high-speed processor applications.

The ultrafast variable time delay we demonstrate is based on optical signal processing using temporal gratings [6]. To describe the new method, we invoke the analogy between spatial diffraction and temporal dispersion. An optical pulse disperses and broadens as a result of chromatic dispersion in a fiber, in the same manner that light from a spatial slit is diffracted into a far-field region [7], [8]. In both cases, within second-order dispersion or diffraction, the far-field patterns are the Fourier transform of the near-fields, namely the original spatial slit or the original temporal pulse. Furthermore, diffraction from a series of spatial slits generates a far-field pattern that is the product of the single-slit diffraction pattern and a multislit diffraction pattern. In direct analogy, dispersion of a coherent array of optical pulses or a temporal grating, when acted on by chromatic dispersion, results in a temporal pattern that is the product of the individual broadened pulse and the multipulse dispersion pattern. As in the case of diffraction patterns, where the shape or position of the central maxima in the interference pattern is related to the slit spacing, the shape and time position of the central maxima in the temporal interference pattern is related to the amplitude and time separation of the pulses in the temporal grating.

As a simple example, we use a model (that will later be verified experimentally) of a transform-limited 2-ps Gaussian pulse that is dispersed in a length of standard single-mode fiber (SMF) to an output pulse-width of 240 ps. Next, we create a coherent pair of these 240-ps pulses, spaced by 7 ps. This pulse pair will interfere and create the interference patterns shown in Fig. 1. Notice that the interference patterns are just a sinusoidal modulation multiplied by the dispersed pulse envelope. The frequency of the sinusoidal modulation is determined by the pulse pair separation. The position of the peaks in these patterns, or the phase of the sinusoidal patterns, is determined by the relative phase of the optical carrier in the two interfering pulses. The difference in relative phase between the top and bottom plot in Fig. 1 is π.

The concept is demonstrated experimentally using the setup shown in Fig. 2. A 2.2-ps optical pulse with a center wavelength of approximately 1550 nm is launched into a 10.6-km spool of standard SMF. That 2.2-ps pulse is broadened to 240 ps at the output from the fiber spool (position A), as shown by the solid curves in Fig. 2. A 4.6-m length of polarization maintaining fiber (PMF) is coupled to the output of the fiber spool. This PMF is used to create two copies of the 240-ps output pulse, spaced by approximately 6.6 ps. A polarizer is used to align the polarization of the two pulses so that they may interfere to create the pattern, as measured at position B, shown by the dashed curves in Fig. 3. The position of the peak in the pattern can be adjusted by changing the optical phase relationship between the two pulses in the array. We change the optical phase between the two pulses by stretching the PMF. The range of achievable delays is limited to approximately half of the dispersed output pulse-width, or approximately 120 ps in this case.

One weakness of the technique as demonstrated here is that the output from the temporal grating stage is not a single pulse. Therefore, as the phase or timing of the central peak is changed, other pulses in the interference pattern change in intensity. In fact, the sinusoidal interference pattern "walks" underneath the envelope of the dispersed pulse pattern as the phase between the two pulses is varied continuously. There are a number of ways to correct this problem. One way is to construct a more

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K. L. Hall and K. A. Rauschenbach were with MIT Lincoln Laboratory, Lexington, MA 02420-9108 USA. They are now with PhotonEx Corporation, Bedford, MA 01730 USA (e-mail: hall@photonex.com).

D. T. Moriarty, H. Hakimi, F. Hakimi, and B. S. Robinson are with MIT Lincoln Laboratory, Lexington, MA 02420-9108 USA.

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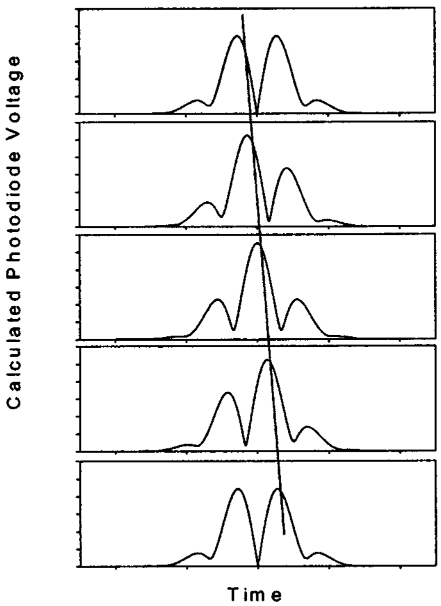

Fig. 1. Simulation of the interference pattern created by a pair of coherent 240-ps pulses with different relative optical carrier phases. The difference in relative phase between the top and bottom plot is π.

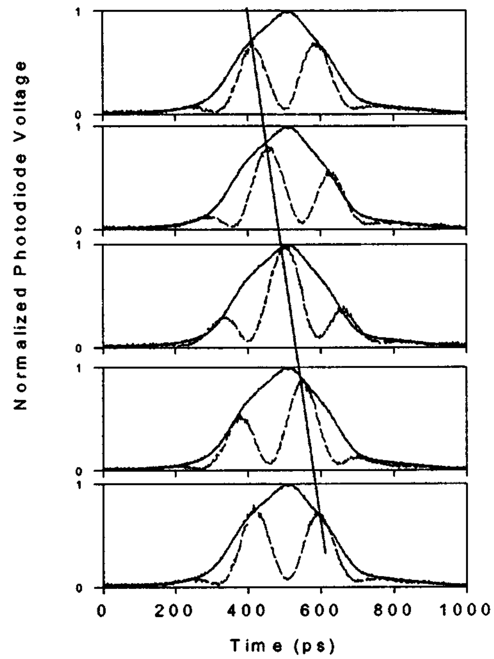

Fig. 3. The two-pulse interference pattern (dashed line) with different relative phase delays. The solid lines shows the output from the fiber when a single pulse is launched.

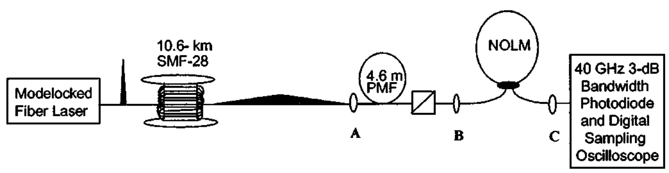

Fig. 2. Experimental setup. PMF is polarization-maintaining fiber and NOLM is nonlinear optical loop mirror.

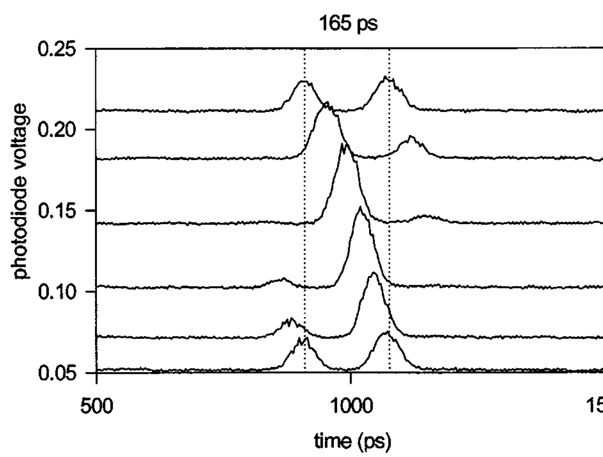

Fig. 4. The time-tunable pulses output from the nonlinear optical-loop mirror acting as an intensity discriminator.

sophisticated temporal grating and tailor the output interference pattern to contain a pulse with a much higher side-mode suppression ratio. Another way is to use an intensity discriminator to select the center lobe in the pattern and extinguish the side-modes. In this experiment, we used a nonlinear optical loop mirror (NOLM) as the intensity discriminator [9]. The time-tunable pulses at the output of the NOLM (position C) are shown in Fig. 4. Notice that the time scale over which the pulses may be tuned while maintaining a large side-mode suppression ratio is much larger in this case.

Because the time delay at the output of the temporal grating is related to the relative optical phase of the two interfering pulses, and because ultrafast phase changes may be induced in electrooptic and nonlinear materials, we believe this technique can produce ultrafast variable optical delay. For example, rather than stretching the (PMF), we used an electrooptic phase modulator at the output of the PMF but before the polarizer in the experiment shown in Fig. 2 to induce a differential phase delay. We observed the same time tunability as described above but on a much faster time scale. The speed of the tuning is this case is limited by the 3-dB bandwidth of the electrooptic modulator and may be as high as 40 GHz, in commercially available components. Ultrafast phase changes similar to those invoked in all-optical switching experiments [10] may also be utilized to produce variable optical delay in the manner described here. Using ultrafast, all-optical effects, tuning speeds of 100 GHz should be possible [11].

In conclusion, we have demonstrated a new technique for achieving variable optical delay. Multiple copies of a dispersed optical pulse interfere and create an interference pattern in time. That central lobe may be time shifted by changing the optical phase relationship of the multiple copies of the dispersed pulse. The tuning speed is determined by the method used to induce the optical phase changes. The magnitude of the time tunability is determined by the amount of dispersion preceding the temporal grating generator. We believe this technique will have many important application areas, including optical networking and signal processing.

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