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Communication with ultrashort pulses and parallel–to–serial and serial–to–parallel converters

D. M. Marom, P. C. Sun, and Y. Fainman

University of California, San Diego
Department of Electrical and Computer Engineering
9500 Gilman Drive, La Jolla, California 92093-0407

A communication method employing ultrashort pulses with parallel-to-serial and serial-to-parallel converters is analyzed in terms of the number of bits that can be encoded in a packet burst, the exact temporal profile of the packet, and the system capacity. The temporal profile of the transmitted pulses is shown to consist of a sequence of chirped pulses, that were also verified experimentally.

The duality between the temporal and spatial frequencies is utilized to convert information from pulsed optical signals to continuous wave (CW) and vice versa[1]. The interference of co-propagating pulses can be recorded on a hologram and read out by diffraction, for time-to-space conversion[2]. The interference of spatial information on a hologram can be read out in time, for space-to-time conversion[3]. By converting a sequence of point sources to a packet of pulses (parallel-to-serial conversion) and then converting the pulses back to the spatial domain (serial-to-parallel conversion), a transmission of spatial information via a temporal channel has been performed[4].

The parallel-to-serial transmitter works as follows (Fig. 1, top): An incident ultrashort pulse's frequencies are modulated by a collection of linear phase functions, generated by the interference of monochromatic beams. By a four-wave mixing (4WM) process the linear phase function of the interference pattern is read out by the incident short pulse. The output is therefor a replication of the input pulse at different time shifts, according to the slope of the phase functions. The generated pulses carry the information to be transmitted, in a format of a packet of bit pulses with on-off keying.

To analyze the temporal output of the resulting pulses, we make several assumptions: frequency ω is replaced by $\omega_0+\delta\omega$ along with the assumption that $\delta\omega<<\omega_0$, a Gaussian pulse envelope function is assumed, and we neglect some edge effects in the aperture function of the output grating. Under these assumptions, the output of the processor is given by[5]

$$s_0(x'';t) = \sum_n A_n \exp[\, j\omega_o t] w''[-x'' - n\Delta''] \frac{1}{\sqrt[4]{1+\xi^2 n^2}} \exp\left[j\frac{\tan^{-1}(n\xi)}{2}\right] \exp\left[-\frac{t_n^{\,2}}{2\tau^2}\frac{1+j\xi n}{1+\xi^2 n^2}\right], \tag{1}$$

where $t_n \equiv t - t_0 - n\frac{\Delta''}{c}$ is the time delay of the n-th pulse or bit encoded (with A_n the binary bit information), and we define $\Delta'' \equiv \frac{\alpha\omega_w\Delta}{\omega_o}$, and $\xi \equiv \frac{2\Delta''}{c\omega_o\tau^2}$, where $\alpha=\sin(\theta)$ with θ being the inclination angle between the incident wave and the reflection grating, ω_w is the frequency of the CW source, ω_0 is the center frequency of the short pulse with time constant τ, Δ is the spatial separation between channels in the spatial domain, and c is the speed of light. Eq. 1 describes a sequence of temporal pulses, each with a slightly shifted aperture position, with a different relative phase and a broadened pulse-width since these pulses are no longer transform limited (i.e., chirped). The amount of chirp increases as n increases, with a positive chirp for n positive and negative for n negative.

The anticipated pulse chirping of the output pulses of the parallel-to-serial transmitter were verified experimentally by cross-correlation measurements with a transform limited pulse (Fig. 2). The traces illustrate that as the pulse is shifted a greater distance in time (corresponding to a greater n), the pulse width increases symmetrically about the center. The Full Width at Half Maximum (FWHM) was used as a basis for comparison between the calculated and measured result. The FWHM in the calculated and measured values are in excellent agreement, proving that the output pulses are chirped, as expected by Eq. 1.

The serial-to-parallel receiver works as follows (Fig. 1, bottom): The incoming packet of bit pulses is Fourier transformed (FT) in the receiver and interfered with a reference pulse on the spectral plane. The interference pattern is read out by a CW beam by another 4WM process. The interference pattern is assumed to correspond only to the interference of the bit pulse with the reference pulse without intersignal interference (interference between different bit pulses in the packet). This assumption is valid as long as the reference pulse power is much stronger than each individual bit pulse in the packet. As a consequence of this assumption, the superposition principle can be used to analyze the interference of a single bit pulse and then introduce the entire sequence. The diffracted CW field contains the information originally transmitted, with optical power on any diffracted order corresponding to the presence of that bit pulse in the sequence.

Again invoking the Gaussian pulse assumption, the resultant diffracted field in the serial-to-parallel receiver is

$$h\left(x^{\dagger}\right)=\sum_{n} A_{n} \exp\left(-\frac{\alpha^{2}}{4\tau^{2}\omega_{o}^{2}}\left(\frac{x^{\dagger}}{\lambda_{r}}+\frac{n\Delta''}{\alpha\lambda_{o}}\right)^{2}\right), \tag{2}$$

which describes a collection of Gaussian spots separated in space. The location of the peak of each diffraction order is at $x^{\dagger}=-n\Delta\frac{\lambda_{r}}{\lambda_{w}}$, where λ_{w} is the CW wavelength used to write the phase function in the transmitter, and λ_{r} is the CW wavelength used to read out the interference of the pulses. The presence of a signal at a diffraction order location n is determined by the information bit A_n. A linear detector array placed at the output plane reads the information packet, with detector response time determined by the time aperture of the grating and not by the duration of the ultrashort pulse (giving rise to a simplified detector response time on the order of 100 ps).

In the analysis, the transmitted signals were not distorted between the transmitter and receiver, where the data is interfered with a local reference pulse. If the data were distorted in transmission by dispersion and other effects, as expected in fiber transmission, the interference at the receiver would not be the required linear phase function and the diffracted field would not correspond to the desired data. By sending the reference pulse on the same optical fiber along with the data at the transmitter, both signals experience the same distortion effect in propagation. The interference signal of the data and reference pulse cancel out all phase variations by the phase conjugation process inherently present in 4WM, and the readout beam is compensated for the distortion. Transmission loss variations across the bandwidth of the pulse can be shown to have a small effect. This self-referencing scheme, has an additional advantage of eliminating the local reference at the receiver. This solves the synchronization problem inherent in any coherent communication system, as a timing misalignment in this system can be shown to give rise to a shift of the diffracted field along the $x^{\dagger}$-coordinate.

To determine the capacity of a fiber link employing a parallel-to-serial transmitter and a serial-to-parallel receiver at its two ends, several additional design issues have to be introduced. The spatial separation in the transmitter parallel channels, Δ, is found by specifying a tolerable crosstalk between channels in the receiver. The number of bit pulses in a packet depends on the numerical aperture of the optical fiber and the diameter of the optical beam, which in tern will also determine the focal length of the coupling lens to the fiber. This analysis will show that, as expected, with short duration pulses (τ small, large bandwidth) more bit pulses can be compressed into a single packet, and furthermore that we can utilize a significant portion of the optical bandwidth as information bandwidth, illustrating the efficiency of this transmission method.

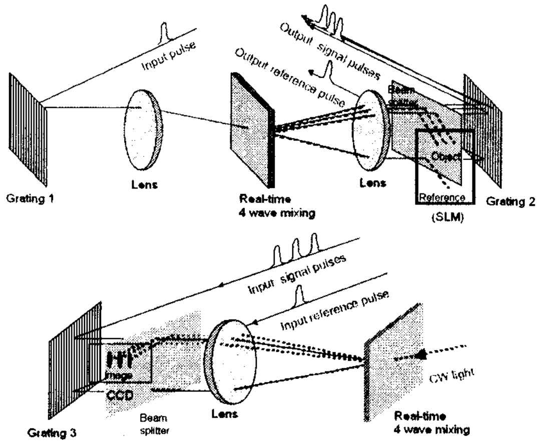

Fig. 1 - Top: parallel-to-serial transmitter
Bottom: serial-to-parallel receiver

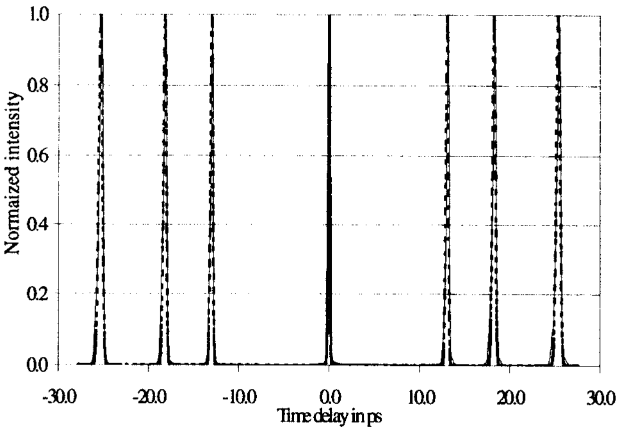

Fig. 2 - Experimental and calculated traces of cross-correlation of output and reference pulses (dashed - theoretical; narrow line - calculated)

References:
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2. Nuss, *et. al.*, *Opt. Lett.* 19, 664-666 (1994).
3. Nuss and Morrison, *Opt. Lett.* 20, 740-742 (1995).
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