

## Synchronization in a Wideband Optical Data Transmission System

**Abstract:** An optical synchronization technique is described for the demultiplexer of a wideband optical data transmission system. In this system, the closely spaced optical pulses of interleaved PCM channels are "space sorted" by a coincidence detection technique using an optical reference waveform generated in the receiver. For synchronization of the reference waveform with a spatial waveform produced by the received laser beam in the demultiplexer, a number of pulses on these two optical waveforms are coded with a pseudo-random sequence. Acquisition of the coded waveforms for synchronization is indicated in an optical matched filter. For automatic tracking, a synchronization error-control circuit is added.

This communication suggests an optical correlation method for synchronization in an optical data transmission system in which many pulse-code modulated (PCM) channels are time-multiplexed [1-3]. In the particular type of system discussed here, the sequence of data pulses transmitted during each time frame is derived from one pulse of a mode-locked laser [4]. Each time frame contains pulses used for the acquisition and error control of synchronization as well as the pulses that are single data bits of the interleaved PCM channels. Optical series-to-parallel conversion in the demultiplexer (see Fig. 1) transforms the received serial data stream into a succession of "spatial waveforms," but only one of the spatial waveforms,  $H_0$ , contains a sequence of pulses that is identical to that in the time frame of a received laser beam. With the aid of an optical reference waveform, which is generated in the demultiplexer and is in synchronism with  $H_0$ , the PCM channels are "space sorted" by coincidence detection [5,6] and the data bits in  $H_0$  are routed to the correct channel receivers.

The problem of synchronization becomes especially important when high channel capacity is desired, since the time-multiplexed optical pulses can be spaced so closely that they cannot be separated by electro-optical techniques. The use of an optical correlation method is one way to solve the problem. In the method proposed here a number of pulses in each frame of the transmitted and reference waveforms are coded with identical pseudo-random sequences [7]. Synchronization is indicated by the autocorrelation maximum, which occurs when the

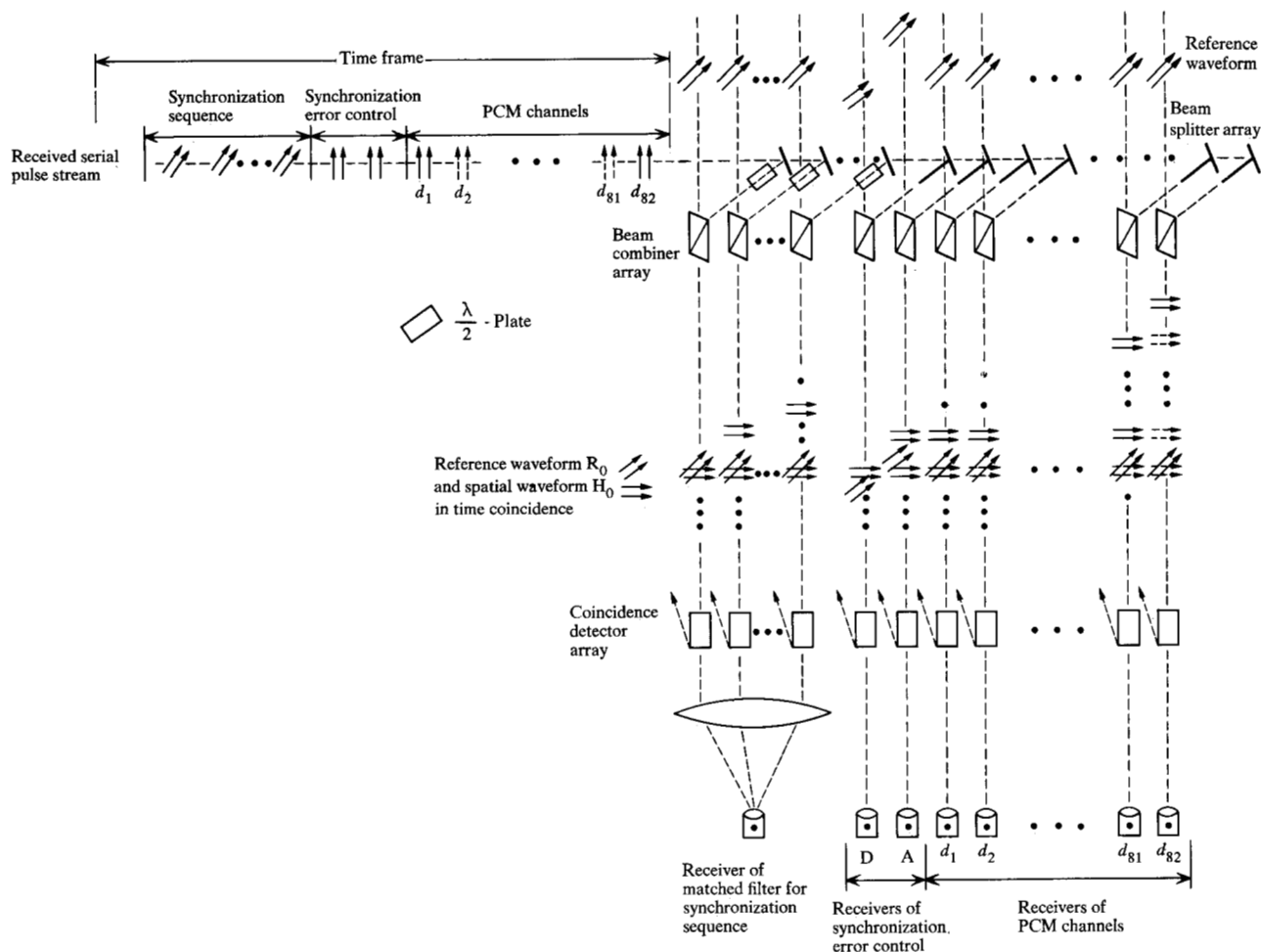
two coded waveforms are in time coincidence. The autocorrelation function of the pseudo-random sequence has the general form

$$C(k) = \sum_{m=0}^{N-1-k} a_m a_{m+k} = \begin{cases} 0 \text{ or } 1 & \text{for } k = 1, 2, \dots, N-1 \\ n & \text{for } k = 0, \end{cases} \quad (1)$$

where the  $a$ 's are either 1 or 0,  $N$  is the length of the pseudo-random sequence and  $n$  is the number of 1's in the sequence. On the coded optical waveforms following the pseudo-random sequence, the 1's are represented by optical pulses and the 0's by their omission. The autocorrelation enhancement when the two waveforms are in time coincidence ( $k = 0$ ), is equal to the number of optical pulses. The subsidiary maxima, which can occur when the two waveforms are offset by  $k = 1$  to  $N - 1$  bit positions, can never exceed one.

We will assume that the correlation method is used in an optical system operating with a continuously mode-locked Nd-YAG laser having a pulse repetition frequency  $f = 200$  MHz and a pulse width  $\tau = 25$  ps. With a separation of 25 ps, the number of time-multiplexed pulses can be 100. Through the use of pulse delay and modulation, the serial stream of data transmitted during each time frame can have the form

$$\underbrace{1 \ 0 \ 1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1}_{\text{synchronization sequence}} \underbrace{1 \ 1}_{\text{synchronization error control}} \underbrace{d_1 \ d_2 \ \dots \ d_{82}}_{\text{PCM channels}} \quad (2)$$



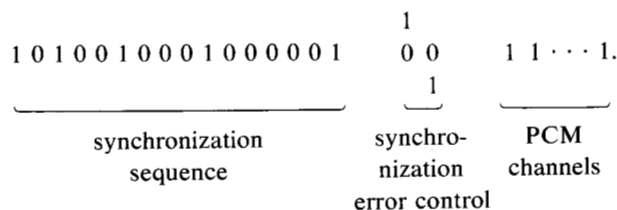
**Figure 1** Simplified diagram of the demultiplexer in which a received sequence of optical pulses is converted to parallel spatial waveforms. Each time frame of the received sequence contains pulses used for acquisition and error control of synchronization, as well as the pulses of the PCM channels, where the full lines represent the +1's, the dashed lines the zeroes. Also shown is an orthogonally polarized spatial reference waveform, generated in the demultiplexer by a mode-locked laser with a pulse repetition frequency identical to that of the laser in the transmitter.

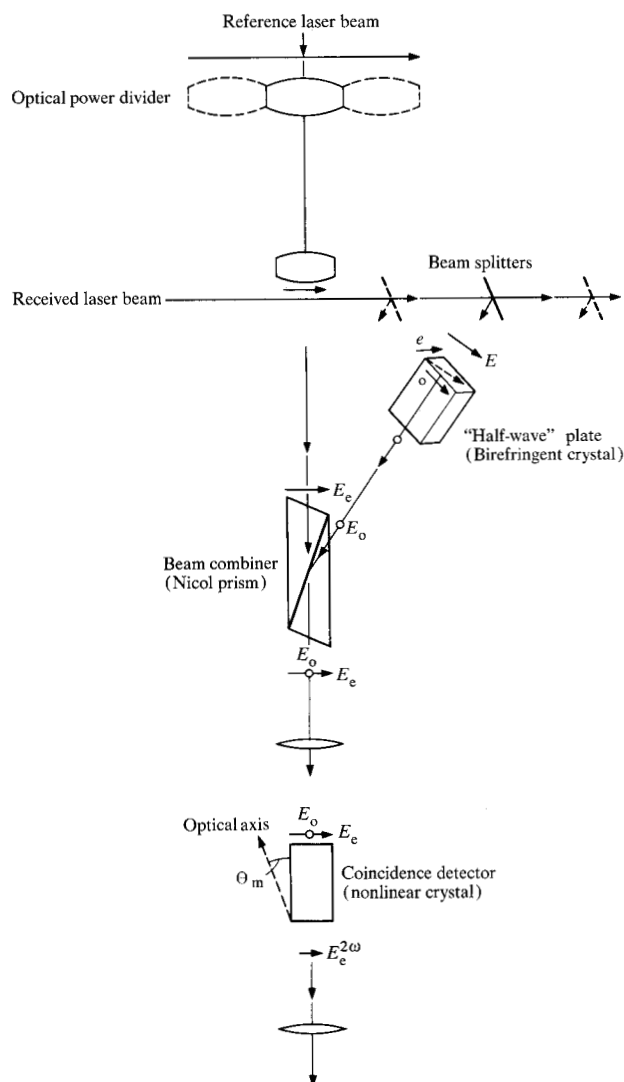
where the data pulses in up to 82 channels ( $d_1, d_2, \dots, d_{82}$ ) are preceded by the pulses in the coded waveform of the synchronization mode and by two pulses devoted to synchronization error control. The coded waveform of five optical pulses follows a typical pseudo-random sequence of 16 bits having the auto-correlation properties of Eq. (1), with its maximum value 5. This coded waveform is used for illustrative purposes, since it keeps the number of bits and of optical pulses small, and still permits good discrimination in the optical system where all optical pulses of the PCM channels and the synchronization error control can be excluded from the correlation process.

The separation of the optical pulses of the synchronization sequence from those of the PCM channels and the error control is accomplished by polarization discrimination in the optical beam combiners of the demultiplexer. For this separation the pulses of the transmitted coded

waveform of the synchronization mode are polarized orthogonally to those of the PCM channels and the error control. In the demultiplexer the sequence of optical pulses on the received laser beam is converted to a spatial function from a time function and then combined with the pulses of the reference waveform in an array of Nicol prisms. However, the pulses can be combined only when they enter the Nicol prisms polarized as ordinary and extraordinary rays, respectively, as shown in Fig. 2.

The sequence of optical pulses on each spatial reference waveform generated in the receiver is





**Figure 2** Polarization of optical pulses in one channel of the synchronization sequence.  $E_o$  is the polarization of ordinary ray and  $E_e$  is the polarization of extraordinary ray.

All reference pulses enter the Nicol prisms polarized as extraordinary rays. For exclusion of all received pulses but those of the synchronization sequence from the correlation process, a birefringent crystal is inserted into the optical paths of the pulses forming the synchronization sequence on the spatial waveform  $H_0$ . The birefringent crystal, shown in Fig. 2, functions as a "half-wave" plate and rotates the polarization of the pulses by 90 degrees, with the effect that the received pulses of the PCM channels and the error control pulses enter the Nicol prisms of the correlator polarized as extraordinary rays, while the received pulses of the synchronization sequence enter these Nicol prisms correctly polarized as ordinary rays.

Time coincidence of the reference waveform with the spatial waveform  $H_0$  is indicated by the auto-correlation maximum in the output of an optical matched filter that intercepts the optical pulses of the combined coded waveforms. The optical matched filter is formed by a coincidence detector array, where the array spacings follow the same pseudo-random sequence as the coded waveforms. The coincidence detectors are nonlinear crystals that generate the second-harmonic wave when the orthogonally polarized optical pulses of the synchronization sequence simultaneously traverse the crystals [8]. The pulses of the second harmonic waves from the coincidence detectors are filtered, collected and focused into a photomultiplier (see Fig. 1).

Because the bandwidth of the photomultiplier is narrower than that of the mode-locked optical pulses, the electro-optical conversion and amplification introduces considerable broadening of the pulses and distortion of their shape. This, in turn, produces an asymmetrical auto-correlation function, whose maximum when the coded waveforms are in time coincidence is, nevertheless, clearly indicated in Fig. 3.

When the maximum in the matched filter output is detected, the received and demultiplexed waveform has been synchronized with the reference waveform. Then the interleaved PCM channels can be "space sorted" by the coincidence detectors associated with the data channels and routed automatically to their correct channel receivers, whose gain is now turned up.

To maintain time coincidence of the two optical waveforms over a limited range, a synchronization error control scheme is proposed. Its general approach is outlined here. The two pulses on the received and reference waveforms that are used for error control cooperate with associated coincidence detectors and photomultipliers. To generate error signals the two pulses on the reference waveform are displaced symmetrically in direction of propagation of the optical waveform by  $(c/n)\tau$ , where  $n$  is the refractive index of the nonlinear crystal (coincidence detector),  $\tau$  the pulse width and  $c = 3 \times 10^{10}$  cm/s. The relationships between the outputs of the two photomultipliers and the time difference between the reference waveform and the spatial waveform  $H_0$  are shown in Fig. 4. When the reference waveform is advanced with respect to the spatial waveform  $H_0$ , the error signal from the photomultiplier A increases until it reaches its maximum value at a time difference equal to the duration of one optical pulse. When the reference waveform is delayed, an analogous situation occurs with the error signal from photomultiplier D.

The gain of the error control amplifiers is turned on only after synchronization is acquired. This gain control performed by the optical matched filter, though essential for the automatic correction of synchronization errors,

restricts the range of error control to plus or minus one pulse duration. The output of the error control amplifiers is fed back to the system where the magnified motion of a piezo-electric transducer can be used to change the position of a corner-cube reflector and, thus, vary the length of the optical path of the reference pulses.

Finally, to determine the feasibility of the proposed synchronization method, we investigate whether the insertion of the coded waveform will reduce the channel capacity significantly. While the length of the pseudo-random sequence obviously subtracts from the number of time-multiplexed pulses that can be allocated to data channels, a more important consideration is to determine whether the coded waveform uses up so much of the power of the continuously mode-locked laser that there is not enough power left for the time-multiplexed pulses of the data channels.

Assuming no transmission loss between transmitter and receiver, the power per pulse, in watts, of the demultiplexed spatial waveform  $H_0$  and the reference waveform is, respectively,  $P_t/M^3$  and  $P_r/M$ , where  $M$  is the number of time-multiplexed pulses in each frame. The power of a second harmonic pulse generated by a coincidence detector, in watts, when the received and reference waveform are synchronized is [9]

$$P_{2\omega} = K \frac{P_t P_r}{M^4} \quad (3)$$

Using a  $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$  crystal of 1-cm length in phase-matching orientation, a 10-cm focal length lens to focus the optical pulses into the nonlinear crystal and using values obtained from Refs. 6, 9 and 10, we calculate a value  $K = 0.1 \text{ W}^{-1}$ .

In the receiver, with the predominant noise being shot noise, the signal-to-noise ratio is [11]

$$\text{SNR} = I_m^2 / \langle (\delta i)^2 \rangle \quad (4)$$

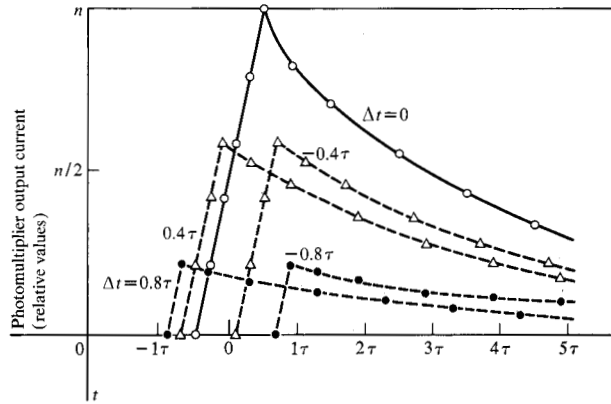
where  $I_m$  is the photomultiplier current and  $\langle (\delta i)^2 \rangle$  is the mean square of the random photomultiplier current fluctuations.

Eq. (4) can be converted to

$$\text{SNR} \approx \eta \pi \frac{P_{2\omega} \tau^2}{h\nu \tau_0} \quad (5)$$

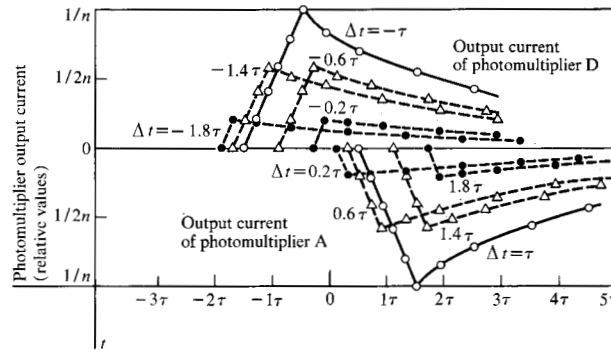
where  $h\nu$  is photon energy,  $\eta$  is the quantum efficiency (it is 15 percent for an S-17 photocathode at 0.53 micron wavelength),  $\tau_0 = 100 \text{ ps}$  is the time constant of the multiplication stages of the photomultiplier and  $\tau = 25 \text{ ps}$  is the pulse duration.

If we wish to achieve a SNR of 30 dB, the above values require that  $P_{2\omega} = 1.5 \times 10^{-4} \text{ W}$ . Consequently, from Eq. (3) the continuously mode-locked lasers in transmitter and receiver for 100 time-multiplexed pulses in each frame must put out a pulse power of at least 400 W.



**Figure 3** Autocorrelation function of optical matched filter. The time constant of the photomultiplier is  $\tau_0 = 100 \text{ ps}$ ; laser pulse duration is  $\tau = 25 \text{ ps}$ ; and  $\Delta t$  is the time difference between the reference waveform and the spatial waveform  $H_0$ .

**Figure 4** Error signals for the synchronization error-control method. The system parameters are the same as those given in the caption for Fig. 3.



There will, of course, be additional losses due to reflection and absorption of the optical components of the system and due to slight misalignment of the nonlinear crystals. Furthermore, transmission losses must also be considered if the transmitter and receiver are sufficiently far apart. Nevertheless, for short distance data transmission there is, clearly, sufficient power to take advantage of a synchronization scheme as described here since a continuously mode-locked Nd:YAG laser is capable of putting out pulse power in excess of 10 kW.

In summary, a technique has been proposed for synchronizing two coded optical waveforms of ultrashort pulses. Time coincidence of the waveforms is indicated in an optical matched filter. Since in the correlation method a timing function is transformed into an amplitude function, the time coincidence of ultrashort pulses can be detected and monitored with a photomultiplier whose bandwidth is considerably narrower than the bandwidth of the pulses.

The characteristics of the optical data transmission system using the synchronization method proposed here seem to make it eligible for data transfer within and between computers. Furthermore, if combined with an optical recirculating delay line, the system could be used to store data as well as demultiplex a high density data stream.

## References

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