Sinusoidal Drives for Optical Time Demultiplexers

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***Abstract*—Electrically driven arrays of optical switches can be used to time demultiplex a train of high-repetition-rate optical pulses into parallel lower speed circuits. These demultiplexers are used to advantage in high-speed communication systems and in photonic analog-to-digital converters. High-speed operation of an optical demultiplexer is simplified by the use of sinusoidal electrical drives, but suppression of crosstalk is difficult. Adequate suppression of crosstalk in these demultiplexers can be obtained through the use additional modulators. The key to our approach is the use of a combination of harmonically related sinusoidal signals applied to the additional modulators in order to select one out of every M pulses. Results with a 1 : 4 demultiplexed photonic analog-to-digital converter operating at 208 MS/s demonstrate the efficacy of the technique.**

***Index Terms*—Analog–digital conversion, electrooptic devices, integrated optics, optical crosstalk, optical switches, time division multiplexing.**

I. Introduction

OPTICAL time demultiplexing can be used to process high-repetition-rate sequences of optical pulses by routing sequential pulses to lower speed circuits operating in parallel. This approach is widely used in high-speed fiber-optic communications [1]–[4]. Optical demultiplexing is also useful for increasing the effective sampling rate of optically sampled analog-to-digital converters [5]–[8]. Development efforts are under way for a new generation of high-sampling-rate analog-to-digital (A/D) converters that exploit the unique features provided by optical sampling of electrical signals. These photonic A/D converters utilize a train of optical pulses to sample an electrical input waveform applied to an electrooptic modulator. The resulting train of amplitude-modulated optical pulses is optically $1:M$ demultiplexed to an array of M parallel circuits where the pulses are detected and their amplitude quantized by conventional electronic A/D converters. Digital interleaving of the quantized samples yields an effective sampling rate that is a factor of M higher than that of the electronic A/D converters. Two types of demultiplexers are being pursued, one based on wavelength-division techniques [7], [8] and one based on optical switches [5], [6], [10]–[12]. This paper focuses on the latter type of demultiplexer.

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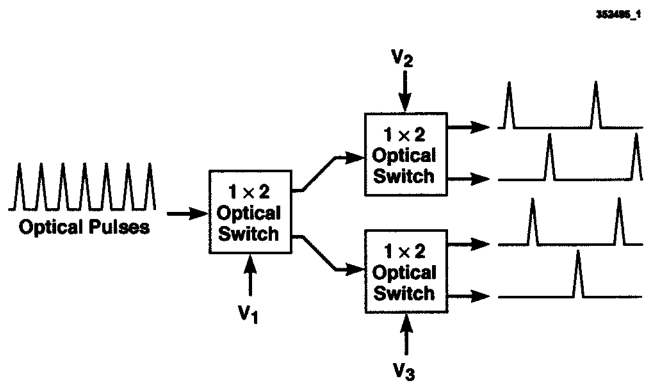

Fig. 1. Standard configuration for a 1 : 4 optical demultiplexer consisting of a binary tree of 1 × 2 electrically driven switches.

A standard type of optical demultiplexer consists of a binary tree of 1 × 2 electrically driven optical switches [3], [4], shown in Fig. 1 for a 1 : 4 demultiplexer. This configuration requires the minimum number of 1 × 2 switches $(M - 1)$ for a $1:M$ demultiplexer. With imperfect switches having finite extinction ratios, there will be crosstalk among the parallel output channels. For this simple configuration, crosstalk may be high because crosstalk is primarily suppressed by only one switch at a time. Such crosstalk can degrade the performance of optical communication systems and limit the accuracy of photonic A/D converters [12]. Typical extinctions for guided-wave optical switches are of the order of 20 to 30 dB. For applications such as high-resolution (e.g., 12-bit) photonic A/D converters where low crosstalk (e.g., 40 dB) is essential, additional devices are required for crosstalk suppression. This paper describes one approach that we have implemented with $LiNbO_3$ guided-wave Mach–Zehnder modulators where four modulators have been added to provide extra extinction (Fig. 2). This approach requires $2M - 1$ switches or modulators for a $1:M$ demultiplexer. Another approach is to use an extra modulator on both outputs of every 1 × 2 switch for a total of 3$(M - 1)$ switches or modulators [10].

The straightforward way to implement the electrical drive signals for optical switches or modulators is to have the voltages switch between the two values that direct the optical pulses upward or downward in the switches or turn the modulators on and off. However, it is increasingly difficult to implement the required high-speed switching waveforms as the input pulse rate increases.

At high speeds, sinusoidal drives become attractive, especially for situations in which short optical pulses arrive at precise intervals [3], [4]. By appropriately setting the dc biases and the ac amplitudes of the drive voltages, the waveforms controlling the switches can be set to be at the appropriate levels for upward

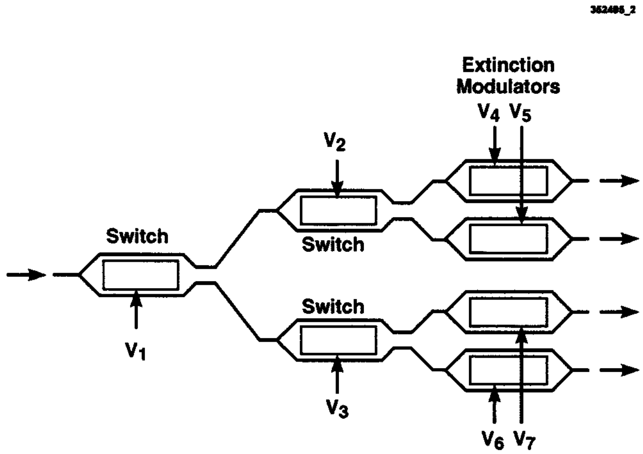

Fig. 2. Layout of a 1 : 4 guided-optical-wave demultiplexer consisting of an array of Mach–Zehnder modulator/switches incorporating 3-dB output couplers. Extra extinction modulators are added at each output.

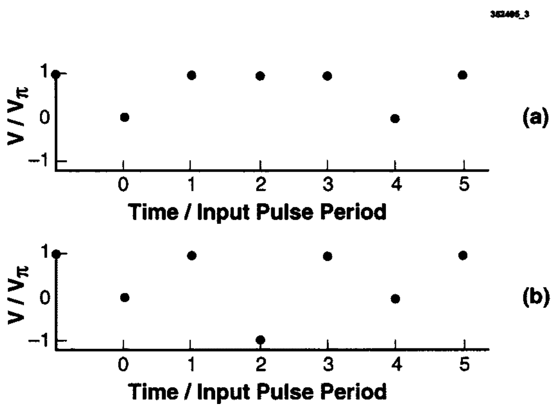

Fig. 3. Drive voltages at pulse arrival times for a modulator that transmits one out of four pulses. (a) Sequence of voltages corresponding to a $k = 0, 1, 1, 1$ sequence. (b) Sequence for $k = 0, 1, -1, 1$.

or downward deflection at the time that the pulses arrive at each switch.

However, a simple sinusoidal drive will not work for the extinction modulators shown in Fig. 2. The function of the extinction modulators is to be on when the desired pulses arrive and be off when other pulses arrive. The challenge is to identify the simplest waveforms that can accomplish this task. If we assume that the modulators are on (transmitting) when V_4 through V_7 are at zero volts, then we want these voltages to equal kV_π where k is an even integer when the desired pulses arrive and k is an odd integer when the undesired pulses arrive. V_π is the switching voltage of the modulators. For a 1 : 4 pulse selector, such waveforms can be implemented by adding two harmonically related sinusoids at frequencies $f_{\rm IN}/2$ and $f_{\rm IN}/4$ along with an adjustment of the dc bias on the modulators, where $f_{\rm IN}$ is the repetition rate of the input pulses. Specifying the voltages of the drive waveforms at the time of arrival of four successive pulses yields four equations in three unknowns. However, there are only three independent equations thus yielding values for the three unknowns, the dc bias and the amplitudes of the two sinusoids. Two of the many possible choices for the sequence of values for k are illustrated in Fig. 3. The corresponding values for the dc biases and ac amplitudes

TABLE I

DRIVE VOLTAGES NORMALIZED TO V_π FOR SINUSOIDAL DRIVE OF A 1 : 4 EXTINCTION MODULATOR

Sequence of Values of k	Amplitude of DC Bias	Peak Amplitude of AC Signal at $f_{IN}/4$	Peak Amplitude of AC Signal at $f_{IN}/2$
0, 1, 1, 1	0.75	-0.5	-0.25
0, 1, -1, 1	0.25	0.5	-0.75

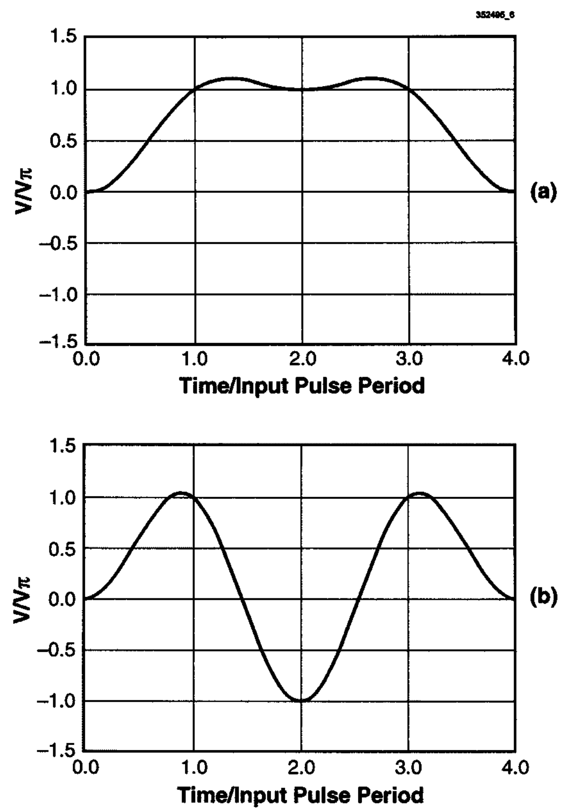

Fig. 4. Extinction modulator drive waveform corresponding to: (a) the sequence $k = 0, 1, 1, 1$ and (b) the sequence $k = 0, 1, -1, 1$.

are given in Table I. The corresponding drive waveforms for the extinction modulators are shown in Fig. 4.

This same approach can be extended to a 1 : 8 pulse selector. The parameters to be set include the dc bias and the amplitudes of ac signals at $f_{\rm IN}/2$, $f_{\rm IN}/4$, and $f_{\rm IN}/8$. Specifying the voltages of the drive waveform for an extinction modulator at the time of arrival of eight successive pulses yields eight equations in four unknowns. There are only five independent equations. A solution is possible only if one equation is ignored which is equivalent to putting no constraint on the voltage at the time of arrival of two pulses symmetrical in time about the fourth pulse after the desired pulse. For a 1 : 8 switch tree, the third and fifth pulses after the desired pulse experience close to the combined extinction of two switches and thus require little further crosstalk suppression by the extinction modulators. For example, a 1 : 8 switch tree consisting of 1×2 switches with 25-dB extinctions will suppress the third and fifth pulses by 41 dB. This means that the extra extinction modulator does not have to provide further suppression of these pulses in order to

TABLE II
DRIVE VOLTAGES NORMALIZED TO V_π FOR SINUSOIDAL DRIVE OF A 1 : 8 EXTINCTION MODULATOR

Sequence of Values of k (* indicates no specification of k)	Amplitude of DC Bias	Peak Amplitude of AC Signal at $f_{IN}/8$	Peak Amplitude of AC Signal at $f_{IN}/4$	Peak Amplitude of AC Signal at $f_{IN}/2$
0, 1, 1, *, 1, * , 1, 1	1.0518	-0.5	-0.25	-0.3018
0, 1, 1, *, -1, * , 1, 1	0.4482	0.5	-0.75	-0.1982
0, 1, -1, * , 1, * , -1, 1	0.5518	-0.5	0.75	0.8018
0, 1, -1, *, -1, * , -1, 1	-0.0518	0.5	0.25	-0.6982

reach a goal of −40-dB crosstalk suppression. Therefore, a judicious choice is to ignore constraints on the voltage on the extinction modulator at the time of arrival of the third and fifth pulses. This leaves four independent equations in four unkowns, the dc biases and the amplitudes of ac signals at three different frequencies. The solutions for various choice of k are summarized in Table II. For a 1 : 16 pulse selector, there are seven independent equations in five unknowns. Solutions require that the specification of the voltages for two pairs of pulses symmetrical in time about the eighth pulse following the desired pulse be ignored. For a $1:M$ demultiplexer, $\log_2(M)$ frequencies are required.

Even though the drive waveforms for the extinction modulators include several frequencies, setting up these waveforms is relatively easy because the overall response of the drive system has to be satisfied at only a few discrete frequencies. These frequencies are the same as those required for the drive of the switches in a demultiplexer. These frequencies can be straightforwardly generated and locked in phase by the use of analog frequency doublers or by digitally counting down from the sampling frequency. By adjusting the amplitude of the signals at the various frequencies before they are combined to drive the extinction modulator, the overall drive levels can be set to compensate for variations in the frequency response of the drive circuitry and modulators.

Because high-frequency Mach–Zehnder modulators typically have values of V_π of a few volts, the electrical power for the drive signals for the switches and extinction modulators can be rather high. However, considerable power reductions can occur if the electrical drivers are resonantly matched to the optical devices [13]. Because each switch is driven at a single frequency, a single-pole matching circuit to the primarily capacitive load of the modulators is adequate. For the extinction modulators, a two- or three-pole resonant circuit can be used for the 1 : 4 and 1 : 8 systems, respectively. Alternatively, the drive electrodes for the extinction modulators shown in Fig. 2 can be split into separate segments with each segment driven at a single frequency through a single-pole matching circuit.

A photonic A/D system incorporating a 1 : 4 sinusoidally driven optical demultiplexer has been assembled and tested [11]. Resonant drives were not used in this initial implementation. The input pulse rate (effective sampling rate) was 208 MHz. An X-cut $LiNbO_3$ demultiplexer incorporating extra extinction modulators in the form of Fig. 2 was fabricated. For the switches and modulators, V_π was approximately 5 V. With the switches and modulator set for maximum transmission to a given output, the

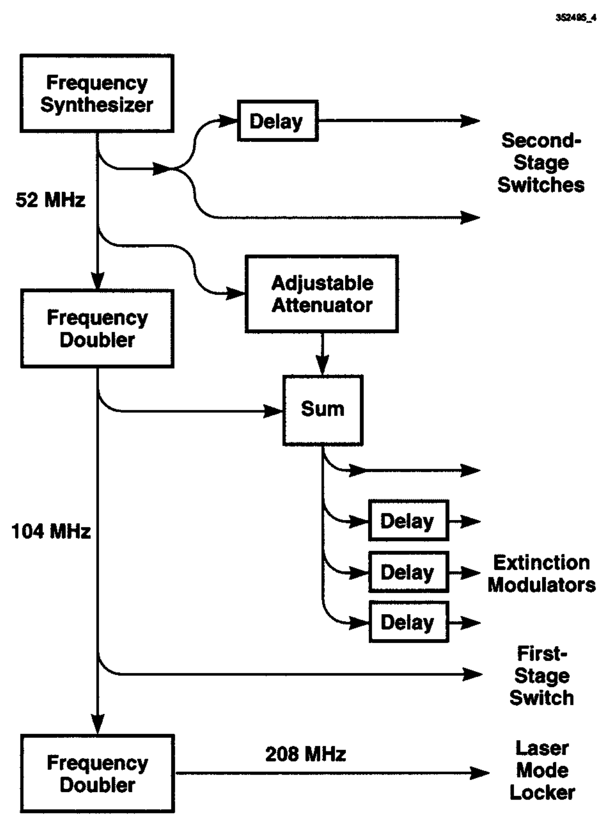

Fig. 5. Circuitry for generating the drive signals for the demultiplexer switches and extinction modulators. Each of the outputs on the right goes through a voltage-controlled attenuator with the voltage supplied by a digital-to-analog converter DAC. The output of the attenuator goes through an amplifier followed by a bias tee with the dc bias controlled by a DAC.

fiber-to-fiber optical insertion loss from the input to output was around 6 dB. The first-stage switch was driven by a 104-MHz sine wave and the second switches by appropriately phased 52-MHz sine waves. The system for generation of the drive signals is shown in Fig. 5. In all cases, the source impedance was 50 Ω and the modulators and switches had a 50-Ω shunt across the device capacitance. The extinction modulators were driven by a waveform corresponding to the 0, 1, 1, 1 sequence illustrated in Figs. 3(a) and 4(a). This waveform was chosen because it required a lower peak-to-peak voltage than the alternatives. The timing of the drive signals relative to the input pulses was precisely established (to within 200 ps) by placing a fast detector at each of the four outputs of the demultiplexer, and observing

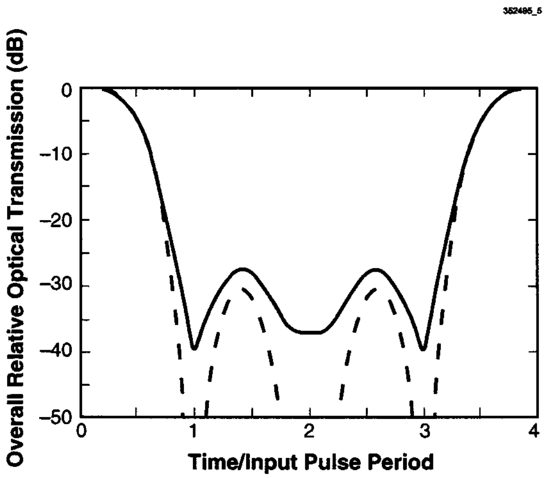

Fig. 6. Calculated overall optical transmission for a 1 : 4 optical demultiplexer incorporating extinction modulators (solid curve). The extinction is assumed to be 13 dB for the switches and 24 dB for the extinction modulators. The dashed curve is the response anticipated for devices with perfect extinction.

the relative heights of the pulses as the ac drive signals to the various stages were switched on and off.

Once system timing was accurately set, the four outputs were attached to detectors followed by interface circuits to the electronic A/D converters. The levels of the dc biases and the amplitude of the ac drive signals for the demultiplexer were controlled by digital-to-analog converters. With a series of constant-amplitude optical pulses input to the demultiplexer, a computer algorithm measured the A/D-converted samples while the dc biases were varied and then set the appropriate dc bias for each device. In a similar fashion, the c amplitudes were varied so as to peak up the desired signals. With an accurately set dc bias, this procedure also maximized the attenuation for the undesired pulses.

After the dc biases and the ac amplitudes were set, the four outputs from the demultiplexer were sent into fast detectors and the output observed on an oscilloscope. By turning on and off the ac drive signals to the various stages, it was possible to measure the extinction ratio for each switch and for the extinction modulators. The switches had optical extinction ratios ranging from 12 to 14 dB. Subsequent switch designs have achieved extinction ratios of around 25 dB. Even this level of extinction would yield crosstalk from the switches alone that would be far too high to meet the −40-dB goal for crosstalk suppression in the A/D converter [12]. Measurements of the extinction modulators alone showed no detectable crosstalk pulses down to the noise level of −24 dB. The combined extinctions of the switches and the extinction modulators (12 dB plus 24 dB) assured that crosstalk is more than 36 dB down. For a demultiplexer with these extinctions, the calculated overall transmission to one of the parallel outputs is shown in Fig. 6. The windows in time over which undesired pulses are suppressed more than 35 dB is much larger than the 30-ps width of the optical pulses employed. Note that the measures for crosstalk suppression are given in terms of ratios of optical powers. The optical detectors, which are square-law devices, yield an electrical output whose crosstalk suppression in dBs in the electrical domain is double the suppression in the optical domain. Therefore, crosstalk voltages at the input to the electronic A/D converters are more than 72 dB down. While operating the demultiplexer, we observed slow drifts of the device bias points over time and temperature that resulted in increased crosstalk. Significant drifts occurred over times ranging from minutes to hours and thus required periodic resetting of the dc biases in order to maintain adequately low crosstalk.

Detailed measurements of the overall photonic A/D converter system showed error spurs at about the −60-dB level [10], [11]. The projected level of errors due to measured demultiplexer crosstalk alone [12] is about −70 dB, thus suggesting that the current limitations on performance are likely due to causes other than demultiplexer crosstalk. The overall performance of the 1-to-4 demultiplexed photonic A/D converter system is discussed in references [10] and [11]. A newer version with higher sampling rate is discussed in this issue [14]. The current performance is comparable to the best conventional electronic A/D converters at similar sampling rates [15]. Further improvements in both the speed and accuracy of photonic A/D converters are expected to extend the performance well beyond the current state of the art summarized in reference [15].

In summary, sinusoidal drive signals are attractive for driving high-speed optical demultiplexers for photonic A/D converters and high-speed optical communication systems. A special class of waveforms consisting of a combination of $\log_2(M)$ sinusoids can be used to drive optical modulators so as to select every Mth pulse out of a pulse sequence. For $M \geq 8$, this approach entails some modest limits on the suppression of certain pairs of pulses in a sequence. An implementation in a 1 : 4 time demultiplexed photonic A/D converter has demonstrated the utility of the approach. Although this paper has focused on the use of special waveforms for driving optical modulators in photonic A/D converters, the approach may be useful for other types of high-speed on–off switches.

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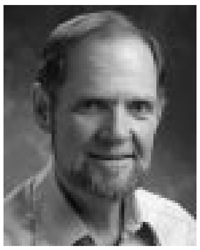

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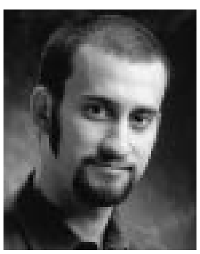

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