Differential processing of ultrashort optical pulses using arrayed-waveguide grating with phase-only filter

H. Takenouchi, H. Tsuda, K. Naganuma, T. Kurokawa, Y. Inoue and K. Okamoto

Differential processing of ultrashort pulses by all-optical time-space-conversion using an arrayed-waveguide grating with a phase-only filter placed along its frequency plane is demonstrated. The experimental results are well-supported by simulations and confirm the feasibility of the process.

Introduction: In future communication systems with > 100Gbit/s data rate, all-optical signal processing devices for 1.55μm will be important. In recent years, pulse pattern generation, waveform shaping and pattern matching, which are difficult for conventional electronic operations, have been achieved using a time-space-conversion technology [1 – 4]. This technology has been successfully demonstrated by using diffraction grating pairs and lenses in free-space optics at visible wavelengths. In this system, however, large diffraction gratings and lenses are necessary to obtain a wide time window, because the size of the components restricts the extent of the window. We have previously proposed a time-space-conversion optical signal processing method employing an arrayed-waveguide grating (AWG), and we demonstrated that optical pulse trains can be generated using an amplitude-only filter [5]. Because the AWG system can provide a flexible choice of diffraction order, we can achieve a wide time window (up to ~1ns). This system can also provide compatibility with fibre optics and compactness. In time-space-conversion optical signal processing, it is necessary to use a phase modulation filter to reduce loss, because an amplitude-only filter often leads to large power losses. The phase filter will also make it possible to apply more complex operations by using computer-generated kinoforms or other optical devices.

In this Letter, we use a phase-only filter for the differential processing of ultrashort pulses to test the feasibility of extending the AWG system to general ultrahigh-speed processing.

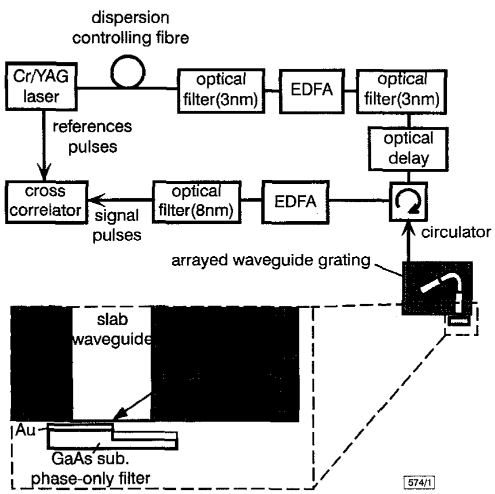

Fig. 1 *Experimental setup for pulse shaping using AWG with phase-only filter*

Experimental results and discussion: We propose a phase-only differential filter, i.e., a step function filter, to advance the differential processing of amplitude envelopes of ultrafast optical pulses. This filter is extracted from the phase component of the exact differential filter, and provides a step-like phase difference of π in the frequency domain. If the centre of the filter is placed at the centre optical frequency, the filter will operate approximately as a differential filter. It has a simple structure and little optical loss. This filter was fabricated by etching a GaAs substrate to a depth of precisely one-quarter of 1.55μm, then Au was deposited. Fig. 1 shows the experimental setup. The AWG was reflection-type and polarisation-independent. The number of waveguides in an array was 340, the diffraction order was 59, and the estimated time window was 100ps. The filter was placed along the frequency plane. The spatial dispersion was 2GHz/μm at the frequency plane. This is sufficient for picosecond-pulse processing because of the ease of fabricating filters by using photolithography. A Cr/YAG laser with pulsewidths of 100fs and a repetition rate of 200MHz was used as a pulse source [6]. The femtosecond pulses were sliced spectrally using an optical bandpass filter and amplified using an Er-doped fibre amplifier. The 1.2ps pulses with a spectral width of 2.2nm and a centre wavelength of 1548nm were input to the AWG. The dispersion of the experimental setup including the AWG was compensated for with a dispersion control fibre. The output waveforms were measured with a crosscorrelator and direct pulses from the laser were used as sampling pulses. Fig. 2*a* and *b* show the measured input and output waveforms. Fig. 2*c* shows the simulated output waveform, using a phase-only filter with step-like profiles (solid line) and an exact-differential filter with amplitude modulation (dashed line). These outputs were calculated from the measured waveform of the input pulse. The calculated results using a phase-only filter in Fig. 2*c* agree very closely with the experimental results. These results, however, are different from the exact differential signal in that the output waveform level did not drop to zero apart from the region of the peak of the pulse.

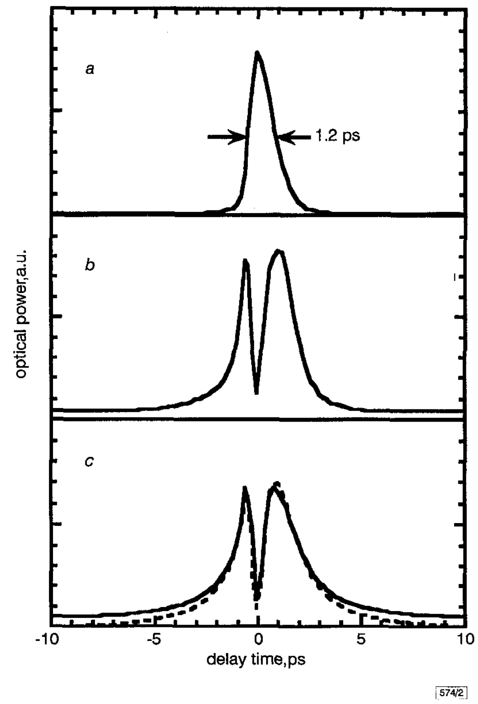

Fig. 2 *Measured input and output pulse waveforms with calculated output pulse waveform*

a Measured input pulse waveform
b Measured output pulse waveform generated by phase-only filter
c Output pulse waveform calculated from input pulse
——— step filter
– – – – differential filter

To estimate the deviation of output pulses between the exact differential filter and the step filter, we used a linear system theory to consider the difference. We assumed the frequency response functions of the exact differential filter and the step filter, respectively denoted $H(\omega)$ and $\tilde{H}(\omega)$:

$$H(\omega) = j\omega \qquad (1)$$

$$\tilde{H}(\omega) = j \cdot \mathrm{sgn}(\omega) = H(\omega) \cdot 1/|\omega| \qquad (2)$$

with $\mathrm{sgn}(x) \equiv x/|x|$. Therefore the electric field of the output signal $g(t)$ is expressed as

$$g(t) = \left[\frac{d}{dt} f(t)\right] * F^{-1}(1/|\omega|) \qquad (3)$$

where $f(t)$ is the electric field of the input pulse. With the step filter, a factor of the inverse Fourier-transformation of $1/|\omega|$ is overlapped to the exact differential output as a convolution operation. The function of $F^{-1}(1/|\omega|)$ is derived approximately as follows:

$$\frac{1}{i\pi}\log|t| + \text{const} \qquad (4)$$

The first term is a sharp function, like the delta function. If an additional convolution factor is exactly a delta function, then the output signal is the exact differentiated waveform itself. Therefore, the output pulses obtained using a step filter have an additional constant term (Fig. 2*c*). The phase-only step filter can thus be substituted for the exact differential filter, which results in more loss.

Conclusions: We demonstrated differential processing of ultrashort optical pulses using an AWG with a phase-only filter, and confirmed the feasibility of processing at 1.55μm. The phase-only filter can be substituted for the exact filter. More complex signal processing for ultrashort pulses can be performed using a higher-phase-level filter. Time-space-conversion optical signal processing using an AWG is a promising method for future ultra-high-speed communications.

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Evaluation of dispersive waves in soliton pulses generated from Mach-Zehnder modulator and singlemode fibre

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Dispersive wave energy included in a soliton pulse generated from a Mach-Zehnder modulator and a singlemode fibre is evaluated. When pulse repetition is 10GHz, the minimum dispersive wave energy is only 0.23% when the pulsewidth is 23ps, and 3% even when the pulsewidth is 13ps.

Introduction: Electro-absorption modulators (EAMs) are often used for generating optical soliton pulses with repetition rates of up to several tens of GHz, because of their integration capability with laser diodes, simple configuration, and stable operation [1, 2]. However, when the EAM pulse shaper is adopted in WDM soliton transmission systems, an EAM is required for every several channels because of the wavelength dependence. Moreover, it has been found that a large EAM loss decreases the signal-to-noise ratio at the optical soliton transmitter and may lead to a decrease in transmission distance [3]. Recently, Veselka and Korotky proposed and demonstrated an optical soliton source using a Mach-Zehnder modulator (MZM) as the chirped pulse shaper and a piece of singlemode fibre (SMF) for chirp compensation [4]. Compared with the pulse source using an EAM, this pulse source has the advantage of low insertion loss and wavelength insensitivity, although the RF driving circuit is more complicated. In this Letter, we evaluate the dispersive wave energy included in the optical pulse generated by an MZM and SMF based on the eigenvalue calculation of the Lax pair equation for the inverse scattering transform (IST) [5] in order to qualify the pulse source for optical soliton transmission systems. We find that the dispersive wave energy is much less than that obtained from the soliton source using an EAM [6].

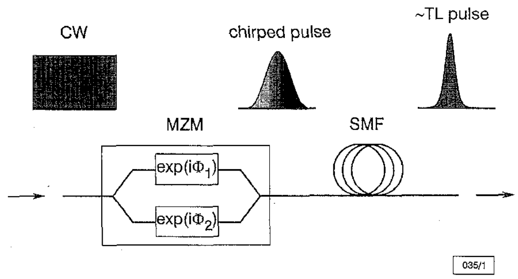

Fig. 1 *Schematic diagram of optical pulse source proposed by Veselka and Korotky*

$\phi_1=(\pi/2)\sin(\omega_m t/2)+\phi_{PM}\cos(\omega_m t)$
$\phi_2=-(\pi/2)\sin(\omega_m t/2)+\phi_{PM}\cos(\omega_m t)$

Calculation of dispersive wave energy: Fig. 1 shows a schematic diagram of the optical pulse source proposed by Veselka and Korotky [4]. Chirped optical pulses are generated by an MZM from continuous waves which are chirp-compensated by the following SMF. The dual-electrode MZM is driven by two RF signals with angular frequencies ω_m and $\omega_m/2$. The $\omega_m/2$ signal is applied in anti-phase to each electrode for intensity modulation. The ω_m signal is applied in in-phase to each electrode for phase modulation to create frequency chirping. Thus, the electric field of the output light of the MZM becomes

$$E_{MZMout} = \cos\left(\frac{\pi}{2}\sin(\omega_m t/2)\right)\exp i(\Phi_{PM}\cos(\omega_m t)) \qquad (1)$$

We first solve a linear wave propagation equation numerically to obtain the electric field of the optical pulse after propagating in the SMF. We assume that the group velocity dispersion of the transmission line is constant and that the system has no soliton control scheme. The energy of solitons included in the pulse can be evaluated by solving the IST eigenvalue equations [5]. The dispersive wave energy E_D is obtained by subtracting the soliton energy from the total pulse energy [6, 7]. Since E_D depends on the pulse amplitude, we choose the pulse amplitude to minimise E_D. We then determine the relative dispersive wave energy ε_D which is the ratio of E_D to total pulse energy. The calculation was made with varying Φ_{PM} and the SMF length L_{SMF} where the repetition rate of the output pulses is 10GHz.

Figs. 2*a* and *b* show the contour plots of the FWHM width of the output pulse and ε_D aganst L_{SMF} and Φ_{PM}. These Figures are useful for designing Φ_{PM} and L_{SMF} with a specific pulsewidth and for obtaining ε_D. Fig. 2*a* indicates that the minimum pulsewidth decreases as Φ_{PM} increases. Note that an ε_D of less than a few percent is achievable in a fairly wide area as seen in Fig. 2*b*. Fig. 3*a* shows the minimum ε_D against Φ_{PM}. The pulsewidth when ε_D is minimum is also plotted. The minimum ε_D of 0.13% where the pulsewidth is 23ps is much smaller than the calculated value for the soliton source using an EAM [6]. Fig. 3*b* shows the minimum ε_D against pulsewidth. When the pulsewidth is < 23ps, the minimum ε_D increases as the pulsewidth decreases. However, ε_D is ~ 3% even when the pulsewidth is 13ps. This fact is an advantage