Asynchronous All-optical Signal Processing Achieved Using Raman Soliton Effect

Masao Kato†

Abstract

Error-free asynchronous all-optical bit-by-bit self-signal recognition and simultaneous demultiplexing have been successfully demonstrated using a signal processor based on the intensity-dependent self-frequency shift induced by the Raman soliton effect. The processor demultiplexed overlapping signals in "contended optical packets" with a recognition sensitivity of better than 3 dB. Clear open eye diagrams were successfully obtained. The ability to achieve three-stage cascade error-free operation was verified. Furthermore, photonic conversion of the multiplexing format from WDM (wavelength division multiplexing) to OTDM (optical time division multiplexing) was experimentally demonstrated. Four WDM channels with a 200-GHz channel spacing were converted into one OTDM signal with various repetition rates of up to 100 GHz.

1. Introduction

Photonic packet-switched networks will be able to support future intelligent systems in which telecommunications, computer communications, and multicasting coexist. These networks will provide a high-speed data rate, format transparency, and configurability, which are needed for converting different data formats. In general, photonic packet-switched networks can be divided into two categories: slotted (synchronous) and unslotted (asynchronous) [1]. Unslotted networks are easier and cheaper to build, more robust, and more flexible than slotted networks. However, in unslotted networks the probability of contention is higher because packet behavior is unpredictable and less noticeable. The term "contended packets" refers to optical packets that overlap in the time domain, which are difficult to recognize and demultiplex without an optical buffer.

Efforts to achieve buffer-free packet contention resolution are focusing on all-optical devices using high-speed optical time-division multiplexing (OTDM). They are faster than electronic circuits and let us use the optical frequency domain for signal processing. However, in conventional all-optical devices, the synchronization of bit frequency and phase requires an extracted electrical clock to drive the optical source and thus generate control pulses for device operation. This will prevent conventional all-optical devices from becoming useful.

One of the most promising ways of obtaining useful all-optical devices is to develop an asynchronous device that operates without synchronization of the bit frequency and phase. My colleagues and I have developed an asynchronous all-optical signal processor based on the Raman soliton effect. This technique has been used for generating only necessary multi-wavelength pulses [2] and for a novel asynchronous all-optical demultiplexer for ultra-fast OTDM transmission, called the AAA-DEMUX [3]. The term Raman soliton refers to a soliton pulse with an intensity-dependent self-frequency shift [4]-[7]. This originates from intra-pulse stimulated Raman scattering. The downshift of a carrier frequency is proportional to the input pulse intensity when the pulse is propagating in a fiber with an anomalous group-velocity dispersion. Therefore, contended optical packets with different amplitude levels are automatically self-sig-

† NTT Photonics Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: katom@aecl.ntt.co.jp

nal recognized and demultiplexed bit-by-bit, depending on the signal intensity.

This paper describes how we demonstrated error-free asynchronous all-optical bit-by-bit self-signal recognition and demultiplexing from contended optical packets without the use of an optical buffer, control pulse or bit-phase synchronization. The measured processing sensitivity was better than 3 dB and the measured BER (bit error rate) shows that we successfully achieved three-stage cascade operation. Photonic conversion of the multiplexing format achieved by intensity-dependent self-frequency shift of Raman soliton is also described. Experimental results show that the novel asynchronous all-optical signal processor is a low-noise device that is promising for use in contention resolution in unslotted photonic packet-switched networks.

2. Operating principle

The principle of the developed asynchronous all-optical processor is amplitude-division demultiplexing based on the intensity-dependent self-frequency shift of gigahertz soliton pulses. The all-optical self-signal recognition and demultiplexing is schematically shown in **Fig. 1**. The frequency shift is caused by intra-pulse stimulated Raman scattering and the downshift of the carrier frequency is proportional to the intensity of the signals propagating in a fiber with an anomalous group-velocity dispersion.

The signal processor is very simple and consists of three components: an erbium-doped fiber amplifier (EDFA), a highly nonlinear fiber for Raman soliton generation (RS fiber), and an optical bandpass filter (OBF) (**Fig. 2**). The amplitude level of each optical signal is used as a label. Thus, all the signals can be automatically converted into WDM (wavelength division multiplexing) signals, according to their amplitude levels. Therefore, this processor can use the optical frequency domain for signal processing.

Low-speed WDM signals with wavelength of λ_1, λ_2, λ_3, and λ_4 are coupled in a photonic converter composed of variable attenuators (VATTs), variable time-shifters (VTSs), a wavelength combiner (WC), an EDFA, and an RS fiber. All the WDM channels are attenuated by VATTs to equalize their amplitude levels. After time shifting, the amplitude-controlled WDM channels are combined by the wavelength combiner and amplified to the Raman soliton power regime of the RS fiber. Since the downshift of a carrier frequency is proportional to the input pulse intensity when the pulse is propagating in a fiber with an

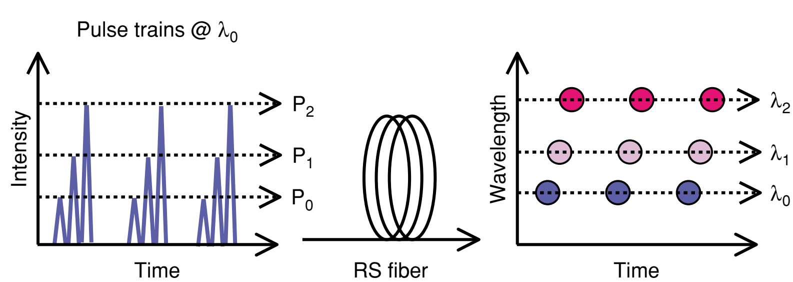


Fig. 1. Schematic concept of bit-by-bit self-signal recognition and simultaneous demultiplexing.

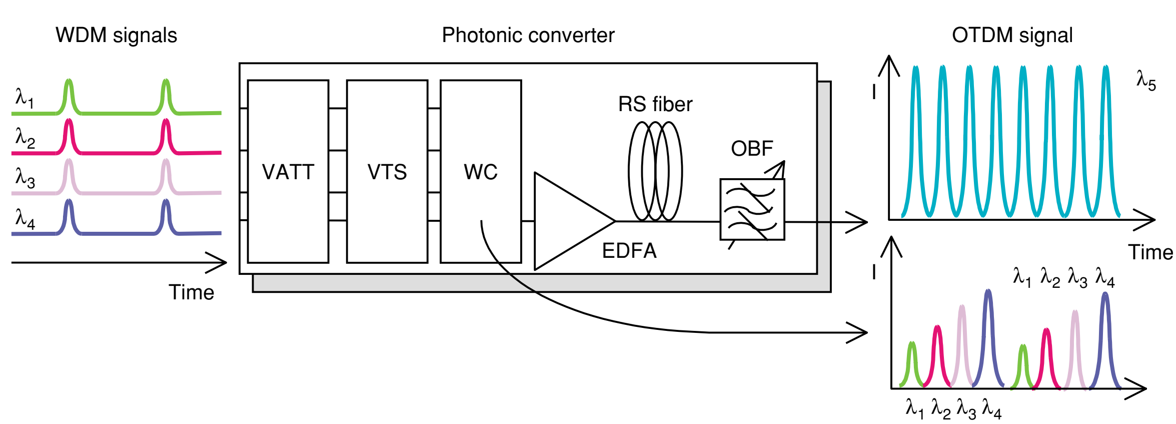


Fig. 2. Schematic configuration of photonic converter.

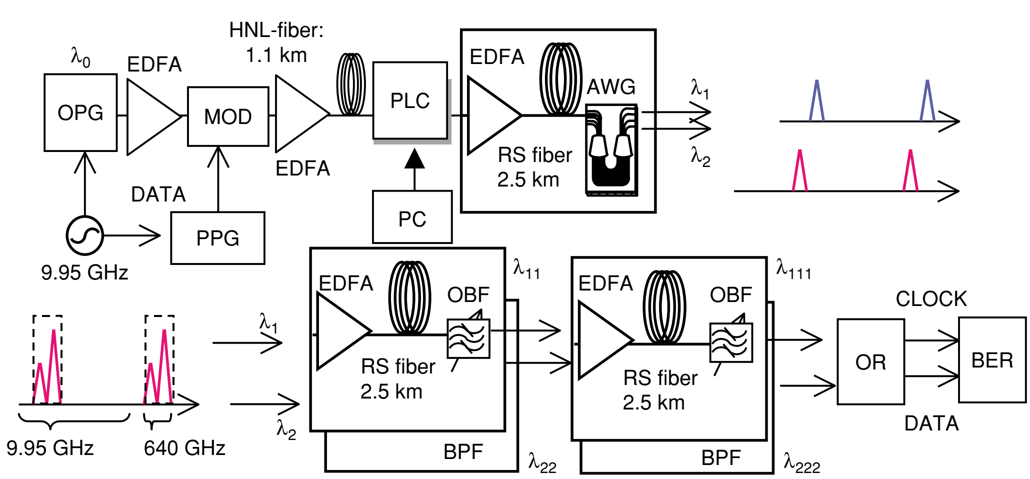
anomalous group-velocity dispersion, WDM channels with different amplitude levels can be converted to the same wavelength (λ_5).

3. Experiment

The experimental setup for self-signal recognition and demultiplexing is shown in **Fig. 3**. A 3-ps, 9.95-GHz optical pulse train at 1555 nm was generated from a newly designed super stable pulse source [8]. The generated pulse train was obtained by synthesizing its Fourier spectrum, which is composed of higher-order sidebands produced by a Fabry-Perot resonator integrated with an electro-optic phase modulator. The train was modulated by a $LiNbO_3$ intensity modulator at 9.95 Gbit/s with a 2^{31}–1 PRBS (pseudo-random bit stream). After coding, the data signal was amplified and connected to a 1.1-km-long highly nonlinear (HNL) fiber. This enabled us to accomplish adiabatic soliton compression to less than 0.8 ps.

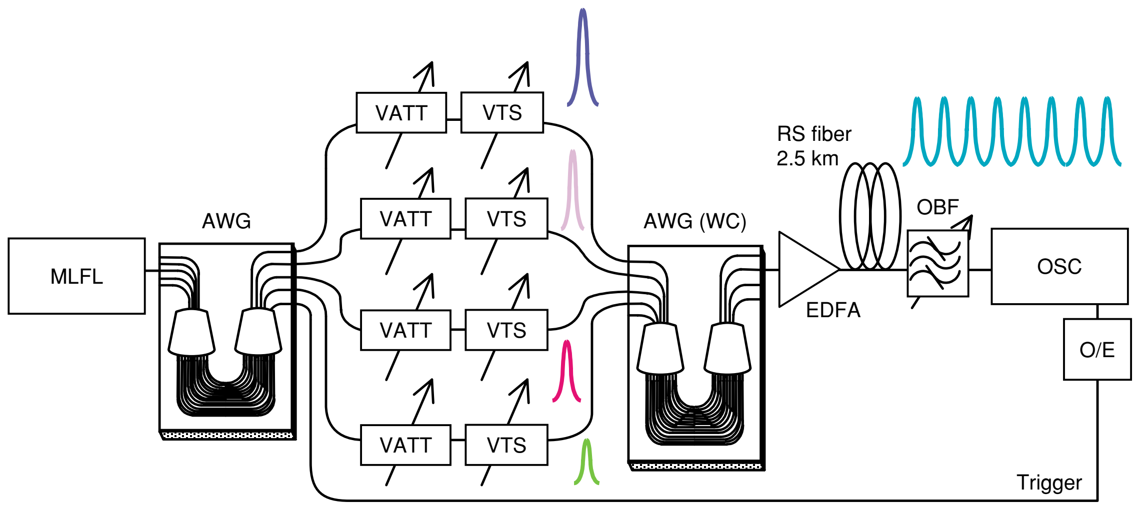
The contended packets are optical packets that overlap in the time domain. Therefore, we emulated the overlapping signals in the contended optical packets using a PLC (planar lightwave circuit) multiplexer with 1.5-ps relative delay lines and a 3-dB relative intensity difference. After overlapping, the contended packets were injected into the processor without synchronization of the bit frequency and phase. The processor consisted of an EDFA, a 2.5-km RS fiber, and an arrayed waveguide grating (AWG) filter with a channel spacing of 200 GHz. To generate soliton pulses, the second-order dispersion of the RS fiber should be positive and, in this case, it was +2.0 ps/nm/km. To verify the capability of cascade operation, we measured the BER performance and eye-diagrams after the signal had passed through three signal processors connected in series. Here, contended packets were not used in the tests for the second and third signal processing stages; instead, OBFs with a 3-nm passband were used in the second and third processors.

The experimental setup for converting the multiplexing format from WDM to OTDM is shown in **Fig. 4**. To generate low-speed WDM channels, we used a repetition rate of 20 MHz, a pulse width of 0.57 ps, and a mode-locked fiber laser (MLFL) with a wide spectrum range of over 9.0 nm FWHM (full width at half maximum). The output spectrum from the laser is shown in **Fig. 5** and the dotted lines show the spectra of WDM channels. We used a pair of AWGs with a 200-GHz channel spacing for spectral slicing, and four WDMs (λ_1: 1556.0 nm, λ_2: 1557.6 nm, λ_3: 1559.2 nm, λ_4: 1560.9 nm) without polarization multiplexing. A 2.5-km-long RS fiber was used and it had a second-order dispersion of +2.0 ps/nm/km at 1555 nm for Raman soliton generation. The experimentally measured dependence of the wavelength shift on input peak power for each WDM channel is shown in **Fig. 6**. These values were all measured in the same way. The pulse widths of input WDM channels 1 – 4 ($\lambda_1 – \lambda_4$) were 4.4, 4.7, 4.7, and 4.7 ps, respectively. It is clear that WDM channels with different amplitude levels can be converted to the same wavelength, e.g., 1575 nm (λ_5). Therefore,



OPG: optical pulse generator, MOD: modulator, PPG: pulse pattern generator, PLC: PLC multiplexer,
PC: personal computer, BPF: bandpass filter, OR: optical receiver, BER: bit error rate test set

Fig. 3. Experimental setup for signal processing of overlapping signals in contended optical packets and for cascade operation examination.



MLFL: mode-locked fiber laser, OSC: oscilloscope, O/E: optical-to-electrical converter

Fig. 4. Experimental setup for photonic converter.

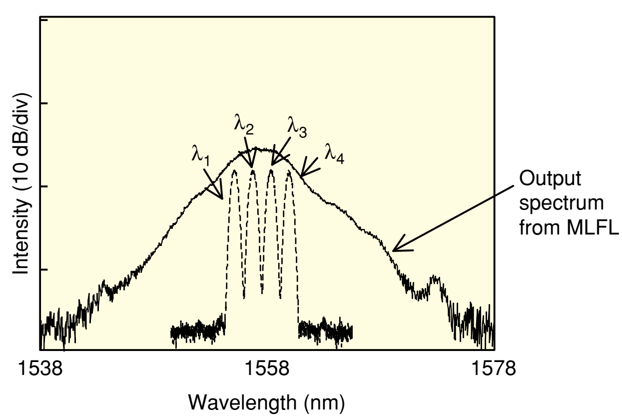


Fig. 5. Spectrum waveform.

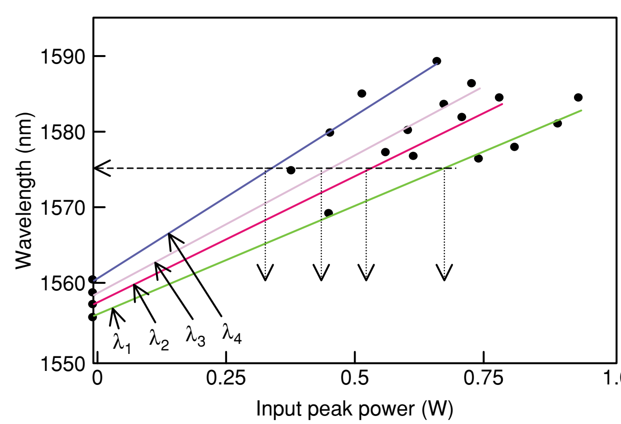


Fig. 6. Experimental dependence of the wavelength shift on input peak power.

the input WDM signals were identically attenuated and time-shifted into various time slots.

4. Results and discussion

Figure 7 shows an autocorrelation trace of the overlapping signals measured after the PLC multiplexer with a relative delay time of 1.5 ps. Signals with a width of 0.8 ps were used and the intensity difference between the overlapping signals was 3 dB. The multiplexed signals are in the longitudinal mode at 640 GHz, which is induced by the relative time delay of 1.5 ps. It should be noted that they cannot be demultiplexed by a bandpass filter. Moreover, they are not easy to distinguish because of the overlapping of the envelope when observed in the time domain. However, after passing through the first processor, the contended signals were simultaneously demultiplexed to 2×9.95 Gbit/s WDM signals at 1561 nm (channel 1) and 1563 nm (channel 2). By using a 3-dB intensity difference as a label, we were able to achieve demultiplexing. Thus, error-free asynchronous all-optical demultiplexing from overlapping signals was successfully achieved without the use of optical buffers, a control pulse, or bit-phase synchronization. The demultiplexed signals exhibited clear eye opening, as shown in **Fig. 8**. They were coupled into the second and third signal processors to examine the possibility of cascade operation. The WDM signals output from the second processor were 1565 (channel 1) and 1576 nm (channel 2) and those from the third processor were 1581 (channel 1) and 1584

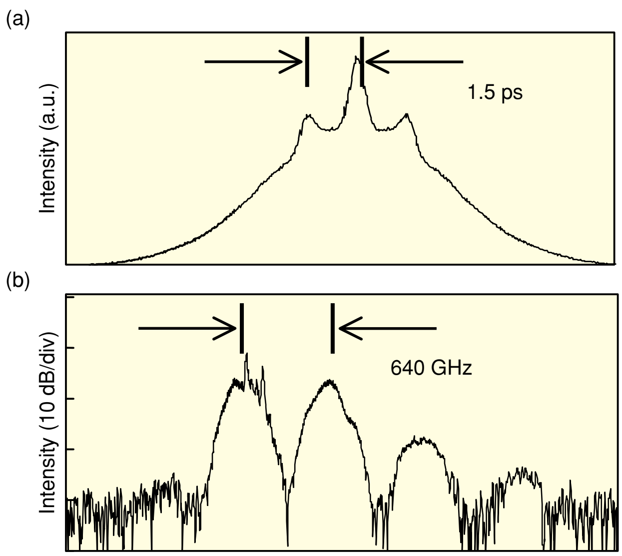


Fig. 7. Overlapping signals with relative intensity difference of 3 dB in contended optical packets. (a) Autocorrelation trace measured after PLC multiplexer with relative delay time of 1.5 ps and (b) spectrum of the overlapping signals.

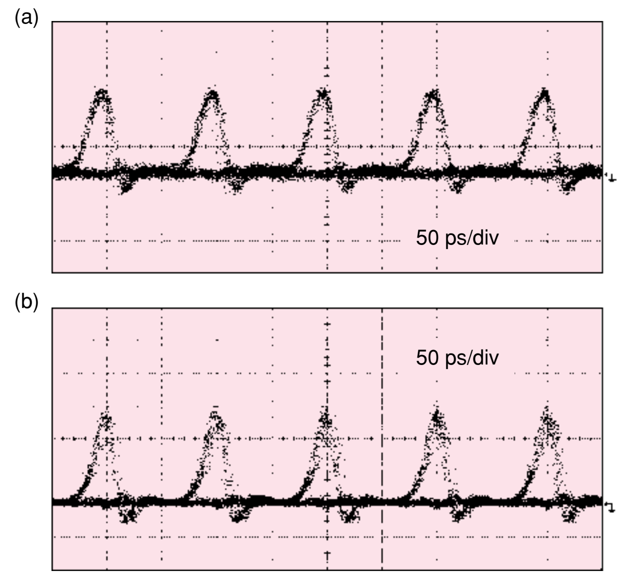


Fig. 8. Eye-diagrams of the demultiplexed signals measured after 1st processor. (a) Channel 1: 1561 nm and (b) channel 2: 1563 nm.

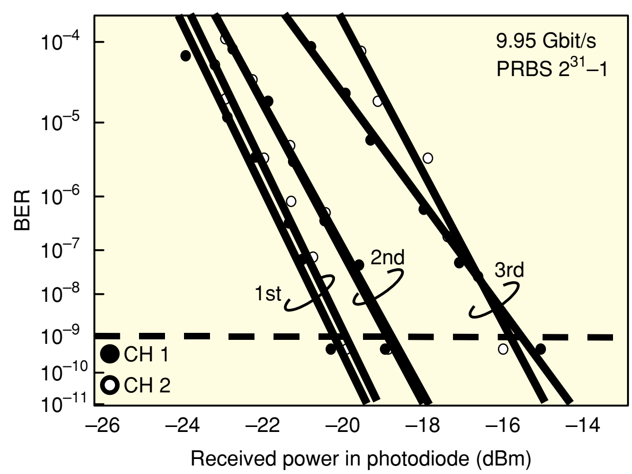
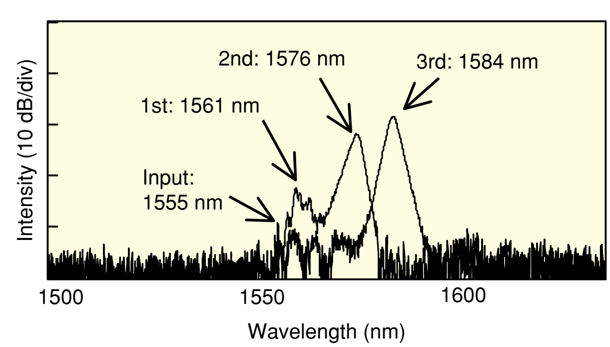


Fig. 9. BER performance measured after 1st, 2nd, and 3rd signal processors.



1st: channel 1, 2nd: channel 2, 3rd: channel 2

Fig. 10. Spectra of the demultiplexed signals measured after 2nd and 3rd signal processors.

nm (channel 2).

Figure 9 shows the BER performance of the demultiplexed 9.95-Gbit/s signals, **Fig. 10** shows the spectra of the demultiplexed signals measured after the second and third processors, and **Fig. 11** shows eye-diagrams measured after the third processor. Clearly open eyes and error-free demultiplexing by the cascade operation were obtained. The power penalties of the second and third demultiplexing stages relative to the first were 2 and 6 dB, respectively, at a BER of 1×10^{-9}. The measured BER performance confirmed a processing sensitivity of better than 3 dB and the ability to achieve three-stage-cascade operation from overlapping signals.

The characteristics of the overlapping pulses were clarified as follows. When the autocorrelation trace of the overlapping pulses was measured, we could not determine whether there was one pulse or a pair of pulses. In general, when a pulse train is divided and multiplexed again with a short delay time, it is difficult to distinguish between one and two pulse trains because of the overlapping of the envelope when observed in the time domain. In this case, observation in the frequency domain provides the required resolution. Since the pulse train is periodic, the spectrum is discrete and the envelope of the Fourier transform is the pulse shape. The frequency spacing is proportional to the repetition frequency of the pulse train. With overlapping pulse trains, the fundamental fre-

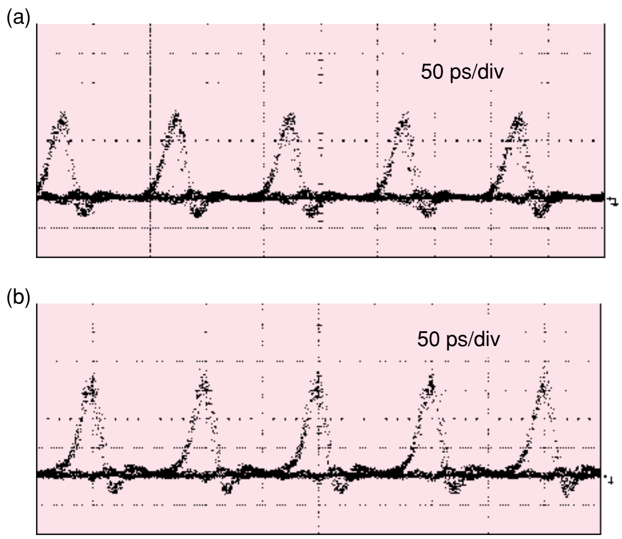


Fig. 11. Eye diagrams measured after 3rd processor.
(a) Channel 1: 1581 nm and (b) channel 2: 1584 nm.

quency of the original pulse train and the frequency synthesized from the overlapping pulse trains coexist in the observed spectrum. In this experiment, the fundamental frequency of the overlapping pulse trains was 9.95 GHz and the synthesized frequency from the overlapping was 640 GHz owing to the time delay of 1.5 ps as shown in Fig. 7(b). Moreover, since uncompressed pulse energy remained around the compressed pulse as a broad pedestal, the waveform of the overlapping pulses was distorted. Therefore, it was more difficult to decide whether there was one pulse or a pulse pair from observations in the time domain.

The output spectrum of the RS fiber is shown in **Fig. 12** and the dashed line shows the spectrum of the amplified spontaneous emission (ASE) of the EDFA measured without WDM signals for comparison. The OTDM signal converted from the four WDM signals was generated at 1575 nm. The output was filtered by a 1.0-nm OBF at 1575 nm to isolate the OTDM signal. **Figures 13(a)** and **(b)** show sampling oscilloscope traces with time separation of 200 and 50 ps, which corresponded to data rates of 5 and 20 Gbit/s, respectively. **Figure 13(c)** shows the autocorrelation trace of the OTDM signal with a time separation of 10 ps corresponding to 100 Gbit/s, which was converted from two orthogonally polarized WDM channels (channels 1 and 2). There are three pulses in the autocorrelation trace and the intensity of the center pulse is twice that of the other pulses; however, this is a feature of the autocorrelation traces of double pulses. The measured pulse width of the generated OTDM

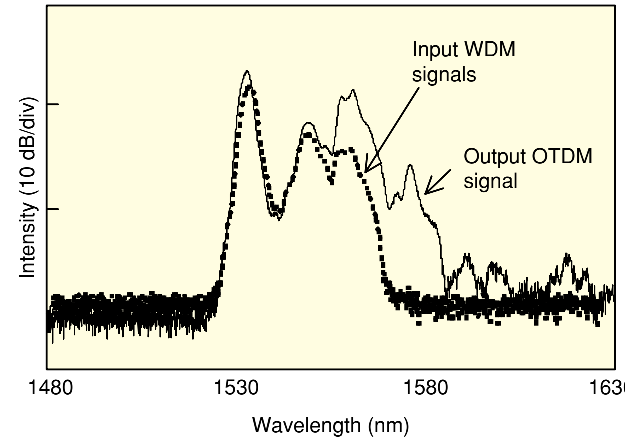


Fig. 12. Output spectrum of RS fiber for photonic conversion.

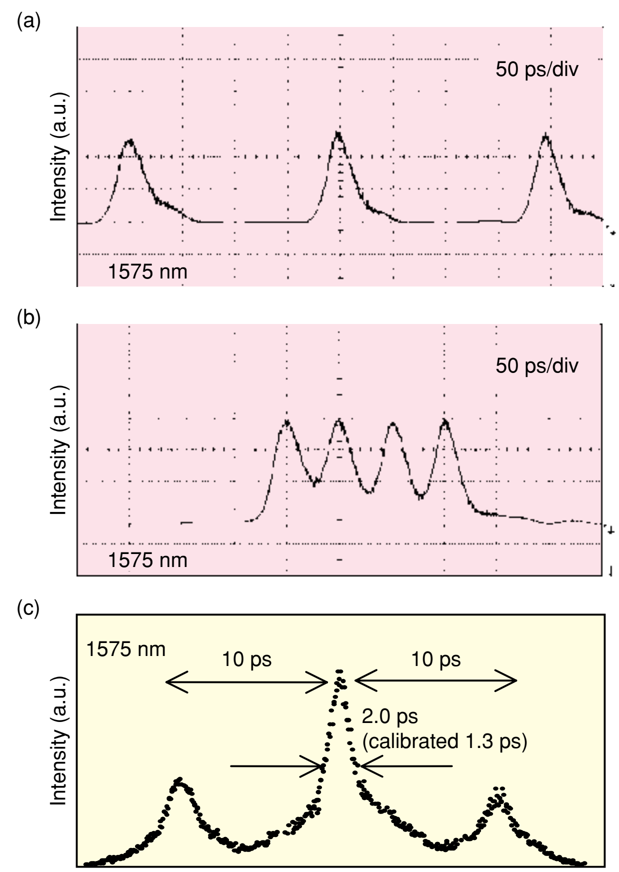


Fig. 13. Converted OTDM signals generated from 4 WDM signals. Time separation is (a) 200 ps (5 Gbit/s), (b) 50 ps (20 Gbit/s), and (c) 10 ps (100 Gbit/s).

signal was 2.0 ps, calibrated to 1.3 ps assuming $sech^2$ pulses. We found that four WDM channels with a 200-GHz channel spacing were successfully converted into one OTDM signal with various repetition rates of up to 100 GHz achieved by the intensity-dependent self-frequency shift of the Raman soliton.

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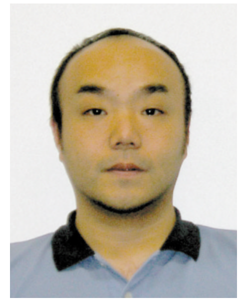

Masao Kato

Research Engineer, Photonic Processing Devices Research Group, NTT Photonics Laboratories.

He is currently taking a Ph.D. degree at the University of Tokyo, Tokyo. He joined NTT Laboratories in 1995, where he was engaged in research on nonlinear optics in optical fiber. Since 2001, he has been engaged in research on all-optical signal processing. He received the 1999 Young Scientist Award for the Presentation of an Excellent Paper from Japan Society of Applied Physics (JSAP). He is a member of JSAP.