Results and discussions: Fig. 3 shows examples of the cumulative chromatic dispersion of the WDM channels. As seen in this Figure, the cumulative chromatic dispersion after 9064km transmission was less than a few hundred ps/nm for all WDM channels. Fig. 4 shows the measured bit error rate (BER) characteristics against transmission distance. A BER of $<10^{-7}$ was achieved for all WDM channels after 9064km.

In our previous, similar experiment using a DSC [4], the capacity was limited up to 100 Gbit/s, and the transmission distance was limited up to 6000km. The reason for the expansion of both capacity and transmission distance can be attributed to the adoption of a low noise EDFA. In [4], the hybrid combination of 1480 and 980nm pumping [9] was adopted, and the 1480nm-pumped EDFA caused degradation of the optical signal-to-noise ratio (SNR) due to the excess generation of ASE noise, compared to the 980nm-pumped EDFA. In this demonstration, only 980nm- pumped EDFA repeaters were employed, and the optical SNR after long distance transmission was improved.

Conclusions: We have successfully demonstrated 213.6Gbit/s, 9064km transmission with 10.66Gbit/s WDM signals for the first time. The key technology for achieving this record was the adoption of the periodic DSC. As the results proved the significance of the periodic DSC for higher bit rate long-distance transmission, it is quite important to develop a wideband DSC that has a simple configuration.

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E-mail: taga@sun6.ebl.lab.kddi.co.jp

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All-fibre-optic clock recovery from non-return-to-zero format data


The authors demonstrate an all-optical clock recovery scheme from non-return-to-zero format data, with an asymmetric Mach-Zehnder interferometer and a mode-locked Er-doped fibre laser. Since this scheme consists of an all-fibre device, the clock recovery bandwidth can extend to the terahertz region. Such all-optical clock recovery techniques will find application in ultra-high speed all-optical communication systems.

All-optical clock recovery will be an essential part of future all-optical communication systems. Most of the reported all-optical clock recovery schemes demonstrated to date have been based on return-to-zero (RZ) format data [1, 2]. However, all-optical clock recovery based on non-return-to-zero (NRZ) format data has been recognised as very difficult to implement because no discretely separated clock component exists in the data. Nevertheless, the NRZ format data is widely used to carry high-speed data and has a better bandwidth efficiency. In the previous works on all-optical clock recovery from the NRZ format data, a non-fibre device, such as a semiconductor optical amplifier, has been used [3, 4]. However, in these schemes, the slow carrier recombination rate of the semiconductor optical amplifier is a main factor limiting the bandwidth to only a few gigabits per second. In this Letter, we demonstrate, for the first time to our knowledge, an all-optical clock recovery scheme based on all-fibre devices from the NRZ format data, by combining a mode-locked fibre laser to a fibre-optic type NRZ-to-pseudo-RZ (PRZ) converter.

To accomplish the all-optical clock recovery function from the NRZ format data it is necessary to process the incoming data in two stages. First, a clock component is generated from the NRZ data stream by using an NRZ-to-PRZ converter based on an asymmetric Mach-Zehnder interferometer (AMZI). Secondly, this clock signal is delayed and then inserted into the fibre laser cavity to generate short optical pulses synchronised to the incoming data. The experimental setup is shown in Fig. 1. An NRZ data sequence was generated by modulating the CW output of a tunable laser diode (HP8168F), whose operating wavelength was set near 1537nm, with an InGaAsP electro-optic modulator driven by a pattern generator. PRZ data was generated from the AMZI, amplified by an erbium-doped fibre amplifier, and then injected into the mode-locked fibre laser. The mode-locked fibre laser cavity consisted of a nonlinear optical loop mirror (NOLM), an Er-doped fibre pumped with a 1480nm laser diode, an optical bandpass
filter F1, and a Faraday rotating mirror (FRM). The cavity was similar to that described in [5], except that the FRM was used as an end mirror, to eliminate the linear phase drift between the two polarisation eigenmodes in the cavity and to deliver environmentally stable outputs. The NOLM consisted of a 3dB coupler FC, a polarisation controller PC, and a 1.6km long dispersion shifted fibre (DSF). The DSF had a dispersion zero wavelength at 1530nm, and connected two identical 1537/1556nm dichroic couplers of WDM1 and WDM2 by forming a closed loop. The dichroic fibre couplers, WDM1 and WDM2, allow the fibre laser to lase at wavelengths in the range 1550–1562nm. The optical bandpass filter F2, which is identical to F1, eliminates the residual 1537nm PRZ pulse signals from the clock output signals.

![Fig. 2 Principle of all-optical-clock recovery from NRZ format data](image)

When the path difference of the optical signals between two arms of the AMZI is $\Delta L$, as shown in Fig. 2a and b, the optical power transmittance $T(t)$ of the AMZI is given by

$$T(t) = \frac{A(t)^2}{4} + \frac{A(t - \tau)^2}{4} + \frac{A(t)A(t - \tau)\cos(\Delta \phi)}{2}$$

$$\tau = \frac{n\Delta L}{c}$$

Here $A(t)$ is an input NRZ data waveform, $n$ is the refractive index of the fibre core, $\tau$ and $\Delta \phi$ are delay time and phase difference between two arms, respectively, and $\lambda$ is the signal wavelength. When the interferometer is biased to satisfy the destructive interference condition, i.e. $\Delta \phi = 2\pi k + \pi$ ($k$ = integer), by adjusting either $\Delta L$ or $\lambda$, the AMZI acts as an exclusive OR gate. Thus, we can convert from the NRZ format to a PRZ format, which contains a clock component, as shown in Fig. 2c. The FWHM of the PRZ pulses is identical to the path delay time $\tau$ between two arms of the AMZI. These PRZ signals are used for an injection locking of a mode-locked fibre laser, to perform a complete clock recovery. The PRZ signals are injected into the NOLM through the coupler WDM1, and ejected by the coupler WDM2 from the NOLM after they affect the propagation property of the intracavity laser light. Then, the reflectivity of the NOLM is modulated by the injected PRZ signals. When the laser round-trip time is a multiple of the modulation period, the mode-locking condition of the laser is satisfied. The continuous pulse stream produced by the mode-locked laser is nothing but the recovered clock signal, as shown in Fig. 2d.

![Fig. 3 Measured oscillograms and RF spectra at each stage](image)

When the path difference $\Delta L$ between two arms of AMZI was 6cm, which corresponds to 300ps delay time $\tau$, the temporal waveforms of the converted PRZ signals are as shown in Fig. 3c. The wavelength of the tunable laser used as the signal light was carefully adjusted near $\lambda$ of 1537nm with the tuning resolution of 0.001nm to obtain the destructive interference condition. The phase difference variation $\delta \phi$ caused by the input wavelength variation $\delta \lambda$, is obtained from eqn. 1 and given by:

$$\delta \Delta \phi = \frac{2\pi n \Delta L}{\lambda^2}$$

(2)

The wavelength variation $\delta \lambda$, of 0.027nm corresponds to $\delta \Delta \phi$ of 2$.\pi$. Hence, a tunable laser with the tuning resolution of 0.001nm was needed to obtain the destructive interference condition. The clock components generated from the NRZ-to-PRZ format conversion can be seen in the RF spectrum of the PRZ data as shown in Fig. 3d. The amplitudes of the PRZ bit stream are irregular due to the loss and coupling ratio differences between two arms of the

AMZI. The average optical powers of the PRZ format data coupled into the NOLM, and that of the clock pulses, were 10 and 0dBm, respectively. The oscilloscope trace shown in Fig. 3e represents the recovered output clock-signal with the mode-locked fibre laser. The mode-locked fibre laser with the PRZ signal injection provides a uniform clock signal stream output. In the corresponding RF spectrum, as shown in Fig. 3f, the signal-to-noise ratio is enhanced by about 10dB as compared to that of the PRZ signal in Fig. 3d. The signal-to-noise ratio may be improved further by stabilising the cavity length, since this can reduce the timing jitter of the mode-locked fibre laser induced from environmental perturbation, such as thermal expansion or mechanical vibration. It is noted that the maximum bit rate to perform the all-optical clock recovery using this scheme is determined by the stored energy in the fibre laser [6]. The wavelength of the recovered clock stream could be tuned continuously within the allowed lasing wavelength range of 1550 to 1562nm for the input NRZ wavelength of 1532 to 1544nm. This method, therefore, can be used not only in NRZ-to-RZ format conversion, but also in all-optical wavelength conversion, and can provide a key process in future all-optical networks.

In conclusion, we have demonstrated an all-optical clock recovery scheme with an AMZI and a mode-locked Er-doped fibre laser, based on an input of NRZ format data. Since this scheme does not use any nonlinear type active device, such as a semiconductor optical amplifier, the clock recovery bandwidth can extend to the terahertz region. Therefore, this scheme of clock recovery may be very useful in ultra-high speed all-optical communication systems.
Experimental setup: Fig. 1 shows the recirculating fibre loop configuration used to test the 1580nm band optical dual-binary WDM transmission performance. The 16 equally-spaced wavelengths (1580.8–1593.1nm), with a separation of 100GHz, were multiplexed using an arrayed waveguide grating (AWG) and simultaneously modulated using a dual-drive intensity modulator with a 2 – 1 pseudo-random bit stream. To generate a chirpless optical dual-binary signal, the modulator was driven with complementary three level signals generated by filtering 10Gbit/s NRZ signals with 2.5GHz lowpass filters (LPFs) [5]. The optical dual-binary signals were then decorrelated in a high dispersion fibre (HDF), which had a total dispersion of –200ps/nm, and boosted by a gain-shifted EDFA (GS-EDFA) [6]. The GS-EDFA had a flat gain region from 1570 to 1600nm. Finally, the boosted signals were introduced into the recirculating loop. The loop consisted of a DSF of 80km in length, two GS-EDFAs, and a gain equaliser. The span loss of the DSF was 18dB. The total fibre input power was +13.5dBm (+1.5dBm/ch). The chromatic dispersion values of the DSF for the WDM signals ranged from 1.3 to 2.2ps/km/nm. The WDM signals output from the recirculating loop were demultiplexed with an AWG and detected with an optical receiver comprising a GS-EDFA, a tunable filter, and a PIN-PD receiver.

Dispersion-compensation-free 16 × 10Gbit/s WDM transmission in 1580nm band over 640km of dispersion-shifted fibre by employing optical dual-binary coding


16-channel, 10Gbit/s optical dual-binary WDM signals in the 1580nm band are successfully transmitted over 640km (80km × 8) of dispersion-shifted fibre with no dispersion compensation or management.

Introduction: In the conventional 1550nm band, the WDM transmission performance of dispersion-shifted fibres (DSFs) is severely degraded by the four-wave mixing (FWM) effect. One way to overcome this problem is to allocate signal wavelengths with unequal channel separations [1]. Since dispersion values at signal wavelengths are very small, this method minimises waveform distortion caused by the interplay between chromatic dispersion and self-cross-phase modulation. However, the number of usable channels is limited to 12 by the bandwidth of erbium-doped fibre amplifiers (EDFAs). Other methods for reducing the FWM effect involve choosing operating wavelengths at which the fibre chromatic dispersion is small, but not zero [2, 3], or using a fibre which has moderate dispersion at the operating wavelengths. Using these methods, the limitation on the number of channels is relaxed, however, the small dispersion at signal wavelengths severely distorts the waveform at bit rates > 10Gbit/s. To overcome this limit, dispersion management or dispersion compensation is needed. Such techniques are not practical for terrestrial systems because the need to adjust dispersion values in accordance with different span lengths in actual transmission lines severely complicates installation and maintenance.

In this Letter, we demonstrate 16-channel WDM transmission at 10Gbit/s over 640km (80km × 8) of DSF without dispersion compensation or management. In our system, the 1580nm band is used instead of the conventional 1550nm band in order to introduce moderate dispersion and so avoid FWM generation. In addition, optical dual-binary coding is adopted to reduce the signal bandwidth by half, to minimise the waveform distortion due to chromatic dispersion [4, 5].

Fig. 3 Q-factor after 640 km transmission

(Q-factor = 10log(Q2))

Fig. 2 Optical spectra before and after transmission

(a) before transmission

(b) after transmission

Power (dBm)

Wavelength (nm)

Fig. 1 Experimental setup for testing transmission performance using recirculating loop