Experimental results: The experimental setup for bidirectional transmission of a 40Gbit/s WDM signal is shown in Fig. 1. It consists of two 8 x 1 AWG multiplexers, two 1 x 8 AWG demultiplexers, two optical booster amplifiers, two optical preamplifiers, and a transmission fibre of 100km DSF. The loss of the transmission fibre is 23dB. The channel spacing of our system is 200GHz and each channel is assigned to a standard frequency proposed by ITU-T. Since the average zero dispersion wavelength of our DSF is 1554.4nm, we allocate channels 3 (1550.92nm) and 5 (1554.13nm) to the up stream signal, and channels 4 (1552.52nm) and 6 (1555.75nm) to the down stream signal, as shown in Fig. 2. By doing this, we minimised the four-wave mixing penalty.

The optical spectrum of EDFA III shown in Fig. 3a shows the transmitted down stream signal (channels 4, 6, 7, and 8) and the Rayleigh back-scattered up stream signal (channels 1, 2, 3, and 5). These signals are demultiplexed by using AWG III after amplification. The output spectrum of the demultiplexer for channel 7 is shown in Fig. 3b. The amplitude of the cross-talk signals due to Rayleigh back-scattering and optical reflection is 30dB less than that of channel 7. It may be noted that the major cross-talk of –22dB at channel 6 arises from the down stream signal component. Thus, the power penalty induced by the Rayleigh back-scattering and the optical reflection is negligible [1, 5].

Discussion and conclusion: The maximum transmission loss of the bidirectional repeaterless transmission system is $C_{awg} - R_{in}$, where $C_{awg}$ is the allowed cross-talk of the system minus the cross-talk of the AWG, and $R_{in}$ is the back reflection coefficient including Rayleigh back-scattering. For our system, the back reflection coefficient and the cross-talk of the AWG are –32 and –22dB, respectively. Thus, the maximum transmission loss is 38dB, when the maximum allowed cross-talk is –16dB (giving a total cross-talk of –10dB for four transmission channels) [5]. Then, the sensitivity of the optical receiver determines the required output power of the transmitter or the optical booster amplifier. The required output power increases as we increase the transmission bit rate; it is 5dBm/channel, when the receiver sensitivity is –33dBm at 10Gbit/s. However, the maximum output power is limited by optical nonlinearity, e.g., four-wave mixing, of the dispersion shifted fibre.

In conclusion, we have demonstrated bidirectional transmission of a 40Gbit/s (4 x 10Gbit/s) WDM signal over 100km of dispersion shifted fibre at ITU-T standard wavelengths. The penalty due to the Rayleigh back-scattering and the four wave mixing are suppressed by using an AWG demultiplexer and proper channel allocation, respectively. The experimental results show the possibility of the high capacity (≥ 80Gbit/s) bidirectional transmission. We can enhance the system capacity by using the periodic property of the AWG without changing the AWGs.

© IEE 1998
27 October 1997
Electronics Letters Online No: 19980160
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References

Fig. 4 Measured BER curves and measured power penalty at BER of $10^{-10}$

- a Measured BER curves
- • back-to-back
- ■ 100km bidirectional

Inset: measured eye diagram after 100km bidirectional transmission

We measured the BER (bit error rate) of the demultiplexed signals, and the results are shown in Fig. 4. The BER curves show no error-floor. The measured penalty at BER of $10^{-10}$ for each channel is shown in Fig. 4b and the maximum value of 0.5dB was observed at channel 3. The difference in power penalty between unidirectional transmission and bidirectional transmission is within experimental error.

The four-wave mixing penalty for the down stream signal (channels 4, 6, 7 and 8) was measured without the up stream signal. The measured maximum power penalty at a BER of $10^{-10}$ was < 0.5dB, when the coupled power to the fibre is approximately 2dBm/channel. However, the maximum power penalty was increased to 3.2dB in unidirectional transmission of channels 4, 5, 6, and 7, although the coupled power is 0 dBm/channel. It may be noted that average zero dispersion wavelength of our DSF is 1554.4nm and it is located between channel 4 and channel 5. The experimental results show suppression of the four-wave mixing penalty in bidirectional transmission with proper channel allocation.

Passive all-optical clock signal extractor for non-return-to-zero signals

Chang-Hee Lee and Hak Kyu Lee

The authors propose and demonstrate a new all-optical clock signal extraction from non-return-to-zero signals for optical clock recovery. The signal extractor is a simple passive optical interferometer based on polarisation maintaining fibre.
Introduction: All-optical clock recovery is a major building block of future all-optical communication systems. Many all-optical clock recovery methods exist for the return-to-zero (RZ) signal [1]. For the non-return-to-zero (NRZ) signal, however, an additional optical nonlinear element, such as a semiconductor optical amplifier [2] or a nonlinear loop mirror [3], is required to extract the clock signal, since the NRZ signal does not contain a clock. Recently, we proposed a passive all-optical clock signal extractor for the NRZ signal [4]. In this Letter, we propose and demonstrate a simple passive all-optical clock signal extractor by using an interferometer based on polarization maintaining fibre. The same clock signal extraction device operated successfully both at 2.5 and 10 Gbit/s.

**Fig. 1** Experimental set-up for demonstration of proposed clock extractor and timing diagram

*a* Experimental set-up

*b* Timing diagram

Operation principle: A schematic diagram of the experimental setup, and a timing diagram of the proposed clock signal extractor are shown in Fig. 1. The device consists of polarisation maintaining fibre and a polariser. To excite both the fast axis mode and the slow axis mode with equal amplitude, the polarisation of the input signal is set to 45 degrees from the fast axis. The propagation delay time between the two signals is approximately half the bit period. The polariser located at the output of the fibre is also aligned to 45 degrees from the fast axis in order to have an interference signal. When the interferometer operates in the destructive interference mode, the proposed device acts like an exclusive OR gate, as shown in the timing diagram. That is, the device converts the input NRZ signal to the pseudo-return-to-zero (PRZ) signal. Thus, we can extract the desired clock from the NRZ signal.

The simulated input and output spectra for a 2^-1 pseudo random signal are shown in Fig. 2. The intensity spectrum of the input NRZ signal (the output of an external modulator) shows no clock component. After conversion of this to the PRZ signal by using the proposed device, we have a clear clock signal with harmonics as shown in Fig. 2a. Since we use coherent interference between a signal and its delay, the clock amplitude may decrease when we use a chirped input signal, such as the output of a directly modulated DFB laser.

To investigate the effects of chirping, we perform a simulation with a directly modulated input signal. We obtain a similar output spectrum, although the directly modulated DFB laser output has a large amount of chirp. The change of the normalised clock amplitude as a function of the chirping parameter (i.e. line width enhancement factor) is shown in Fig. 2b. For simulation, we fixed the phase difference between two propagation modes to π, i.e. the destructive interference condition, when the chirping parameter is equal to zero. The clock amplitude changes periodically as we increase the chirping parameter. The period increases when the delay time decreases. For a given chirping parameter, we can maximise the clock amplitude by adjusting the phase difference between two propagation modes. That is, the optimum phase difference for the maximum clock amplitude is a function of the chirping parameter. For practical application, a low speed phase control loop is required to maintain the clock amplitude. The well known control loop for a tunable Fabry-Perot filter is sufficient for this application.

**Fig. 2** Input and output intensity spectra of clock signal extractor

*a* For externally modulated 10Gbit/s signal

- - - - input

- - - output

*b* Normalised clock amplitude against chirping parameter for directly modulated 2.5Gbit/s signal

- - - - 200ps

- - - - 100ps

Experimental results: To demonstrate the proposed device, we performed our experiment using the set-up shown in Fig. 1a. The time delay between the fast axis mode and the slow axis mode is approximately 50ps. The input signal is an externally modulated 10Gbit/s NRZ signal. The chirping parameter of the modulated signal is equal to unity. The length of the pseudo-random binary sequence of the input signal is 2^21 - 1. We used a polarisation controller to launch both propagation modes with equal amplitude. The measured output waveforms are shown in Fig. 3a; when the polariser is aligned to the fast or slow axis of the fibre, we obtain the waveforms shown on the left. By aligning the polarisation axis of the polariser to 45 degrees from the fast axis, a clear PRZ signal is obtained. The input NRZ signal has no clock component, as seen in Fig. 3b. However, after conversion of this NRZ signal to a PRZ signal using the proposed device, we have a clear clock signal as shown in Fig. 3c. We also demonstrate the clock extraction function at 2.5 Gbit/s with the same device. This means that the proposed device can be applicable at any bit rate between 2.5 and 10 Gbit/s.

Discussion and conclusions: The performance of the clock extractor demonstrated in this Letter depends strongly on the input signal polarisation, since we use polarisation maintaining fibre. However, the polarisation dependence can be suppressed by using a polarisation independent asymmetric Mach-Zehnder interferometer, such as an integrated optic type [4] or a conventional fibre type.

The electrical conversion of an NRZ signal to a PRZ signal is becoming a hurdle for high speed optical receivers. For example, electrical exclusive OR gates faster than 20Gbit/s are still in the research stage [5]. However, the proposed clock extraction device
is very simple and passive, thus, it may present a solution to clock signal extraction in those systems. To obtain an electrical clock signal, we halve the output of the optical preamplifier which is commonly used in high-speed optical receivers, and use one as an input signal for the clock signal extractor located in front of the electrical clock regenerator. The output of the clock extractor is converted to an electrical signal using a high-speed photodetector with a narrowband matching circuit, that has a centre at the clock frequency.

![Graph showing waveforms and spectra](image)

Fig. 3 Measured waveforms and spectra

a) Waveforms at different output polarisations

b) Input spectrum

c) Output PRZ spectrum

Inset: measured output PRZ spectrum at 2.5 Gbit/s

Extracted clock signals show 20 dB signal-to-noise ratio, when resolution bandwidth is 1 MHz.

In conclusion, we have demonstrated a new passive all-optical clock signal extractor for NRZ signals by using an interferometer based on polarisation maintaining fibre. The proposed clock signal extractor can be applicable for clock recovery both in all-optical regenerators and electrical regenerators.

Acknowledgment: A part of this work is supported by the Opto-Electronics Research Center.

References


Very high gain, high sensitivity, 40 GHz narrowband photoreceiver for clock recovery

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A 40 GHz photoreceiver has been implemented by cascading on a single alumina substrate a fast side-illuminated AlGaAs/InP pin photodiode, and three narrow-band amplifier chips, based on a 0.2 μm gate length GaAs pHEMT technology. The package was especially designed to suppress parasitic cavity-resonances. The photoreceiver current gain is 57 μA, and the average input noise is < 30 μV/Hz over the 3 dB bandwidth of 40.4 – 41.4 GHz. This is believed to be the highest photoreceiver gain ever reported in a single compact metal package at such a high frequency.

Introduction: In 40 Gbit/s optical time domain multiplexing systems (OTDM), the clock recovery consists of tapping a small amount of the received optical power (< 10%), to feed a phase lock loop (PLL), which generates a 10 GHz clock. For that purpose, the function of the photoreceiver is to detect and amplify the 40 GHz (actually 39.813 GHz) clock frequency contained in the RZ 40 Gbit/s transmitted signal spectrum. The photoreceiver has to provide both high gain and high responsivity at 40 GHz. Moreover, to obtain optimal performances, the photodiode has to be close to the first amplifier for good and reproducible matching; this leads to a compact and potentially low cost module.

The amplifier circuit design and chip characteristics have already been reported [1]. The centre frequency of the amplifiers is tunable over a 38 – 45 GHz band. The gain of one amplifier chip is 18 dB at 40 GHz, with a 2 GHz bandwidth. The technique used is the fully stabilised D02AH technology (0.2 μm gate-length) from Philips Microwave Limb. The transition frequency of the transistors is 55 GHz.

Photodiode: To achieve high speed and high responsivity, a side-illuminated AlGaInAs/GaInAs pin photodiode has been developed. The structure comprises an undoped GaInAs absorption layer sandwiched between two AlGaInAs optical confinement layers, n- and p-type doped, respectively, providing improved coupling efficiency with the optical fibre. The photodiode responsivity has been simulated using mode formalism and BPM in order to optimise the epitaxial structure. The fabrication process uses conventional contact lithography and lift-off techniques, and air bridges are used to reduce the photodiode parasitic capacitance. The fabricated devices exhibit responsivities as high as 0.8 A/W at 1.55 μm, with negligible polarisation dependence (< 0.5%), using a 3 μm diameter lensed fibre and short devices (< 30 μm) [2]. Fig. 1 shows the photocurrent against fibre position for the two axes parallel to the input facet: an alignment tolerance of ±0.7 μm is