Multi-format all-optical-3R-regeneration technology

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Amount of information flowing through the Internet is growing by about 40% per year. In Japan, the monthly average has already reached 3.7Tb/s as of May 2011[1). Considering the explosive spread of smartphone use now underway, the growth of information flow through the optical network is expected to be greater than ever before.

From this background, there is strong demand for faster, power-saving optical transmission system. Until now, due to the very high carrier frequencies of optical signals, using a simple OOK (On-Off Keying) that assigns binary signals to the presence or absence of electric field strength was sufficient for achieving higher speeds. Unfortunately, electrical circuits that perform signal generation are reaching their speed limit. In order to meet the above mentioned requirement, multi-level modulation such as QPSK (Quadrature Phase Shift Keying) and digital coherent technologies are currently being used to put 100Gb/s transmission systems into practical use. However, with optical fiber transmissions exceeding 100Gb/s, power per bit decreases resulting in severe signal degradation due to noise. Optical fiber specific degradation factors such as dispersion and polarization mode dispersion (PMD) also significantly affect signal making reception difficult.

For this reason, large-scale optical networks with transmission distances extending several thousand kilometers require 3R repeaters. 3R refers to the three signal regeneration functions (Re-amplification, Re-shaping, Re-timing) of an optical repeater. To perform 3R, optical-to-electrical signal conversion, signal processing and electrical-to-optical signal conversion are necessary, but as mentioned previously, limitation in processing speed of the electrical circuits makes regeneration process difficult with speeds exceeding 100Gb/s.

If 3R can be achieved without electrical processing (optical 3R), the problem will become easier to resolve, and this viewpoint is the reason 3R regeneration using optical processing technology is attracting attention. Optical processing technology using nonlinear effects such as with an optical fiber has been shown to be capable of switching operations reaching 640Gb/s. Optical signal processing using a similar technology is expected to be applicable to ultra-fast optical 3R. Furthermore, optical 3R regeneration does not perform power-losing OEO conversions, and therefore advantageous from a power-saving point of view. In future optical networks, as services diversify, optical signals are also expected to show diversification, so an optical 3R technology that flexibly responds to different modulation schemes and transmission speeds is desired.

This article introduces initiatives aimed at achieving, with optical signal processing, 3R regeneration capable of ultra-fast processing beyond 100Gbit/s and flexibly supporting different modulation formats.

Elemental Technologies for Ultra-Fast Optical Signal Regeneration using Optical Processing

Figure 1 shows the functions and configuration of an optical 3R regenerator that can be applied to both OOK and (B)PSK ((Binary) Phase Shift Keying) formats. This configuration uses OOK-optical 3R configuration consisting of an optical clock recovery unit and optical logic gate as a base. Implementation of a PSK-OOK conversion (demodulation) function at the front-end enables functional expansion for PSK signal regeneration[2). Although our study includes other technical developments such as adaptive PMD compensation[3) and optical signal monitoring[4) to ensure stable regeneration operation, this article will focus on the following core technologies.

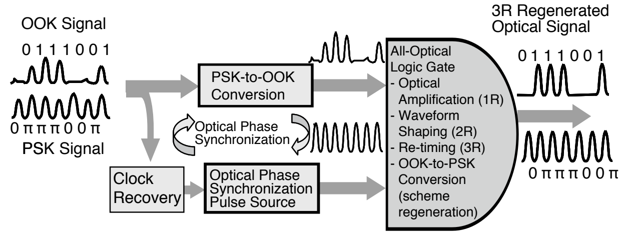

Figure 1. Configuration of a Multi-Format All-Optical-3R-Regenerator

1) 100Gb/s+, optical logic gate technology with powerful signal regeneration effect and OOK/PSK conversion function (scheme regeneration function)
2) Optical PLL (Phase-Locked Loop) technology (homodyne coherent demodulation technology) for PSK/OOK conversion

100Gb/s+, Optical Logic Gate Technology

Figure 2 is a configuration diagram of an optical logic gate that utilizes the high-speed nonlinear effects of optical fibers. The logical gate has a hybrid configuration between a wavelength converter that uses self-phase-modulation (SPM)[5] and a timing/format regenerator that employs a nonlinear optical loop mirror (NOLM)[6]. Wavelength converter in the first stage applies a desired wavelength shift (8 ~ 9nm) to the incoming OOK optical signal (in the case of BPSK, equivalent to the demodulated signal). In the timing/format regenerator that follows, optical recovery clock having the same center wavelength as the input signal is all optical modulated to OOK or (B)PSK using the wavelength converted signal for the control signal.

First, the operation of the wavelength converter will be described. When a strong optical signal enters the optical fiber, a change occurs in the refractive index of quartz, which is the material of the optical fiber, resulting in a nonlinear effect called self-phase modulation. This self-phase modulation produces a new frequency component in the optical signal. The signal's center frequency can be converted by cutting out the signal that has spread over the frequency axis using a center frequency different from the original carrier frequency (it is well known that frequency and wavelength are inversely related when the medium's light speed c/n (n is the refractive index) is constant, therefore converting frequency is the same as converting wavelength, and from hereafter the term wavelength conversion will be used). Also known is that cutting out the area with linear frequency changing yields good waveform reshaping effect. Since the wavelength converter handles high nonlinearity, a specially designed highly non-linear dispersion flattened fiber (HN-DFF) is used. Obtaining high conversion efficiency, the wavelength converter is a two-stage design[7].

The timing/format regenerator is composed of two polarization beam splitters (PBS), a polarization maintaining highly nonlinear dispersion flattened fiber (PM-HN-DFF) and a half-wave plate. Configuration is characterized by the use of a PM-HN-DFF placed inside the loop of a nonlinear optical loop mirror with one of the polarization beam splitter (PBS-2) as the input/output. Polarization of the signal light incident on the loop is rotated as it passes through the half-wave plate, and that angle is dependent on the optical axis angle of the half-wave plate. Since the half-wave plate's optical axis can be easily rotated, difference in rotation angle of this optical clock's polarization is utilized to make all-optical switching of PSK and OOK modulations possible[6].

For OOK operation, optical recovery clock is made to propagate clockwise and counter-clockwise in the fiber loop by adjusting the optical axis of the half-wave plate (there is a place in the loop where polarization is rotated 90°, and optical path lengths of both propagation components are always equal). In the case of PSK operation, optical axis of the half-wave plate is matched to the optical clock polarization and propagated only in a clockwise direction.

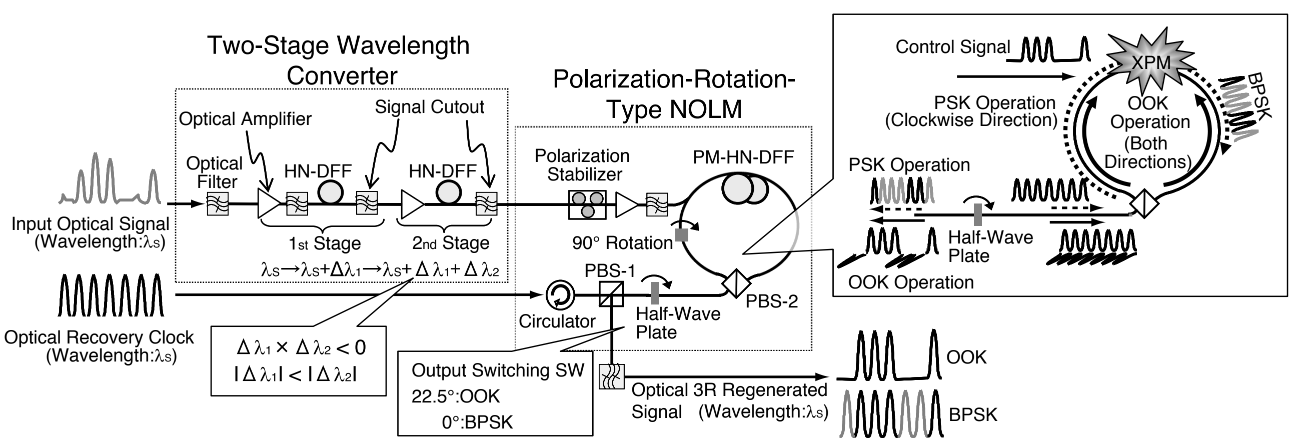

Figure 2. Wavelength Converter with Self-Phase Modulation and Timing/Scheme Regenerator with Nonlinear Optical Loop Mirror

Wavelength converted OOK signal is input as a control signal into the nonlinear optical loop mirror in a clockwise direction. Since control signal pulse intensity is relatively strong, the refractive index of the fiber changes when a control signal pulse is present and a nonlinear phenomenon called cross-phase modulation occurs. As a result, the optical clock input in the right-hand direction is introduced with phase modulation. When control signal pulse is not present, there is no phase modulation.

In OOK operation, the optical clock that has propagated from two directions is polarization synthesized at the loop output to become a polarization modulation signal. Since this signal is polarization separated at PBS-1, just one of the polarization components can be retrieved and OOK optical 3R signal is obtained. In the case of PSK operation, BPSK signal from cross-phase modulation is output as it is. As described above, optical 3R function is obtainable by combining a wavelength converter with a timing/format regenerator.

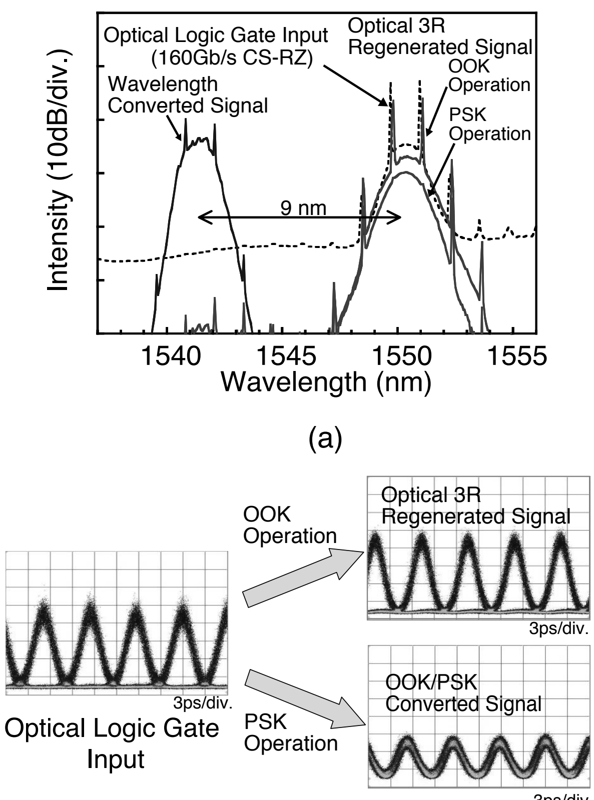

Figure 3. 160Gb/s Optical Logic Gate Operation
(a) Optical Signal Spectrum,
(b) Optical Signal Waveform

Figure 3 is an example of OOK-optical 3R regeneration (OOK operation) and OOK-PSK conversion (PSK operation) when 160GB/s CS-RZ (Carrier-Suppressed Return-to-Zero) signal introduced with noise is input into the optical logic gate of **Figure 2** and show the desired operations are obtained. Additionally, the Q-factors, which indicate signal quality, calculated from bit-error-rate (BER) measurements show improvements of approximately 7dB for OOK and over 3dB for PSK proving good regeneration operations are being achieved.

Validity of optical 3R regeneration for OOK signal has been verified in a field experiment using the JGNII (Japan Gigabit Network II) optical test bed[7]. **Figure 4** is the performance validation result of an optical 3R regeneration applied to a 160Gb/s signal that was transmitted over a distance of 381km (63.5km x 6 spans). Optical signal regeneration has restored signal quality to a level comparable to that of the signal prior to transmission leading us to believe 100Gb/s+ ultra-long transmission is possible by carrying out optical 3R regeneration in multiple stages.

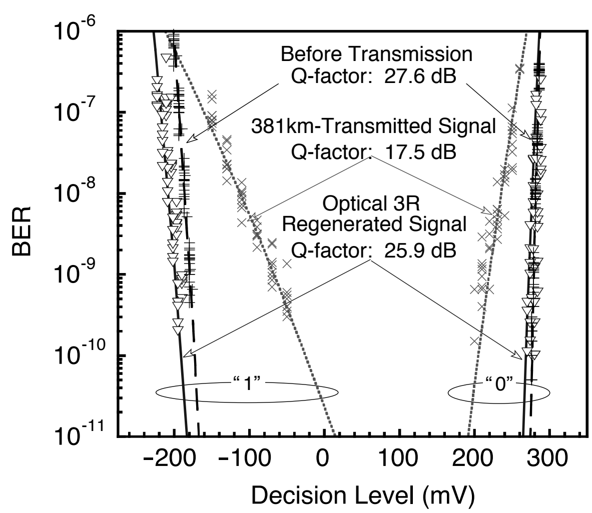

Figure 4. Experimental Result of 160Gb/s-OOK Optical 3R Regeneration using JGNII Optical Test Bed

BPSK/OOK Conversion using Optical PLL Scheme

As mentioned in this article's introduction, in order to achieve optical 3R regeneration of BPSK modulated signal, a scheme conversion which converts phase information of the BPSK signal to direct light intensity information, that is a demodulation technique for the optical domain, is required. Here, we describe the coherent homodyne demodulation technique using optical PLL circuit shown in **Figure 5**. In coherent homodyne demodulation using optical PLL, the BPSK optical signal's phase noise (jump in carrier phase) and shift in carrier frequency are demodulated by generating an accurately tracking local light through negative feedback control and causing an interference to this and the signal light.

In general, light source used for local light generation is independent from the signal light source, therefore there is no phase noise correlation between the two. For this reason, even a local light source of narrow spectral line width (<100kHz) with small phase noise places a heavy load on the negative feedback control, and in particular, the carrier frequency shift (frequency detuning) of both light sources that appear as phase displacement becomes a big disturbance factor in the stability of the phase synchronization operation. To avoid the problem, the optical PLL circuit in **Figure 5** uses an optical injection-locked MLLD (Mode-Locked Laser Diode)[8] for the local light source. Optical injection-locked MLLD outputs an optical signal with the same carrier frequency as the externally input optical signal. When this characteristic was utilized to eliminate the frequency detuning problem, stability of the demodulation process significantly improved[9]. In an experiment on a 40GB/s NRZ-BPSK signal, this scheme was confirmed to provide stable error-free demodulation. However, for stable operation of the optical injection-locked MLLD, BPSK signal's degree of modulation needed to be kept below 90% to maintain the carrier component. Stable demodulation at 100% modulation is a subject for future study. Also, demodulation of the targeted 100GB/s+ has been confirmed by minimizing the loop delay of the optical PLL circuit.

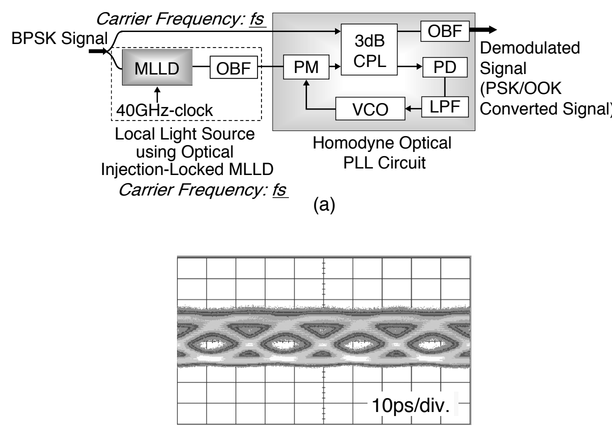

Figure 5. (a) Homodyne Optical PLL Circuit with Optical Injection-Locked MLLD Local Light Source
(b) Demodulated Waveform of 40-Gb/s NRZ-BPSK Signal

TIPS

【Glossary】

Optical 3R
Technology to perform the three regeneration functions of the network node, (amplification: Re-amplification, waveform shaping: Re-shaping, bit interval adjustment: Re-timing) using optical signal processing.

Self-phase modulation
Nonlinear optical effect observed when strong light is input into an optical fiber. Change to the refractive index of the quartz in the fiber changes the phase of the propagating light.

Cross-phase modulation
Nonlinear optical effect observed when two or more wavelength of light is present, and change to the refractive index of one light causes phase change in another light.

Dispersion
Variations in optical signal wavelength result in different refractive indexes which in turn cause differences in speed. Depending on the length of the fiber, effect can occur in a band as small as one channel of the propagating optical signal.

MLLD (Mode-Locked Laser Diode)
A semiconductor laser with a modulator region. It outputs a pulse that is synchronized with the electrical or optical input signal.

Summary

Due to the non-intervention of electronic processing, optical processing has long been a promising technology for providing ultra-fast, power saving processing operations. However, in order for optical processing technology to fully contribute to future optical networks, which will have a wide variety of services, development of a general-purpose technology applicable to various optical signals will be required. As part of that effort, OKI developed a 100Gb/s+ optical 3R regeneration technology that can be applied to both OOK and BPSK modulation schemes.

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