Digital Coherent Receiver Technology for 100-Gb/s Optical Transport Systems

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Digital coherent receivers are expected to be the most important building block of 100-Gb/s optical transport systems. As a platform for evaluating their real-time operational stability and thus helping to realize product-level reliability, Fujitsu Laboratories and Fujitsu have fabricated a test circuit to implement basic algorithms such as carrier phase recovery and optical frequency offset compensation. The experimental results showed an excellent bit error ratio performance that is only 1 dB away from the theoretical limit.

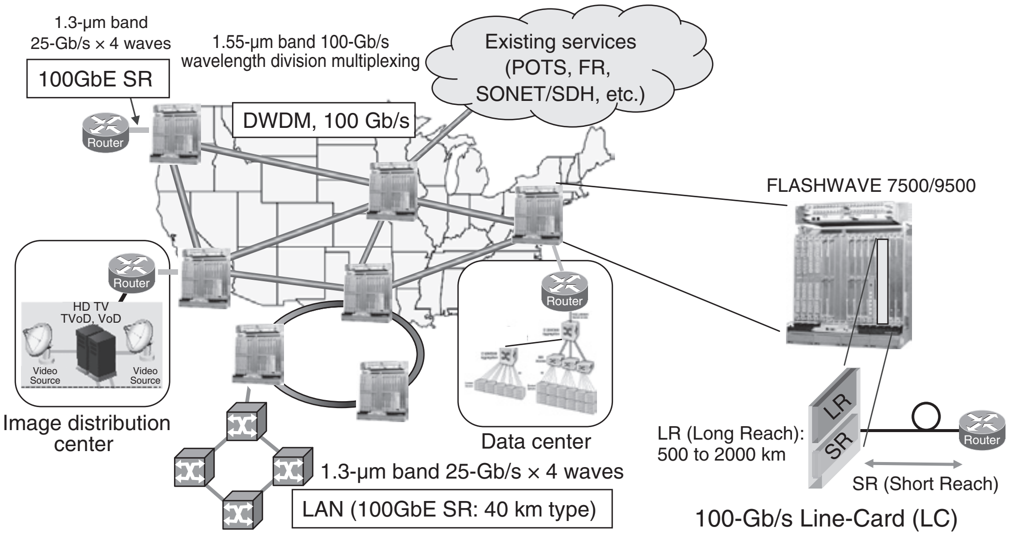
1. Introduction

The communication traffic volume handled by trunk optical transport networks has been increasing year by year, and has quadrupled in the past three years. This volume increase does not only involve a quantitative increase of voice and low-speed Ethernet signals (GbE and 10GbE), which is conventional traffic, but also a qualitative change of increased speed of client signals to accommodate (**Figure 1**). High-volume routers located in large data centers and image distribution centers, which are major traffic generators for today's networks, shall be equipped with high-speed interfaces such as 100 Gigabit Ethernet (100GbE) under standardization by IEEE. Future transmission equipment will need to be capable of efficiently accommodating such high-speed conventional traffic and conventional traffic offering inexpensive long-haul transmission.

For the realization of a 100-Gb/s optical transmission system that meets these requirements, a digital coherent receiver system[note 1)] is a technology expected to serve practical purposes (**Figure 2**). With the 40-Gb/s wavelength division multiplexing transmission system using a direct receiver system[note 2)] that is now in practical use, various optical dispersion compensation technologies are used to manage different types of waveform distortion generated in the transmission lines. With a transmission rate of 100 Gb/s, however, the amount and accuracy of compensation achievable with such optical dispersion compensators have reached their limits. The digital coherent receiver system is capable of offering high-accuracy and wide-range compensation of waveform distortion beyond the limits of optical dispersion compensation, and enables smaller optical dispersion compensators and optical amplifiers that are used to compensate for the losses, which opens up the way to having smaller and cheaper

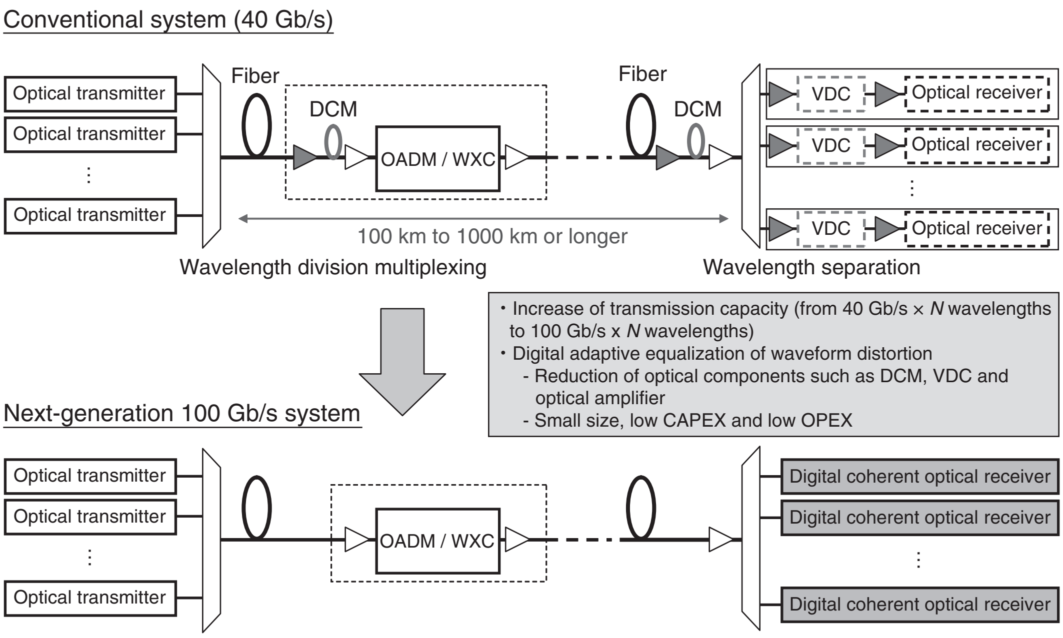
note 1) A method in which information on both optical amplitude and phase is converted into a current for reception.

note 2) A method in which only optical amplitude information is converted into a current for reception; it has proved popular so far because of its simple configuration.



100 GbE: 100 Gigabit Ethernet
DWDM: Dense Wavelength Division Multiplexing
FR: Frame Relay
POTS: Plain Old Telephone Service
SDH: Synchronous Digital Hierarchy
SONET: Synchronous Optical Network

Figure 1
Applications of 100-Gb/s optical transport.



DCM: Wavelength dispersion compensation module
OADM: Optical add-drop multiplexer
VDC: Variable dispersion compensator
WXC: Wavelength cross connect

Figure 2
Typical configuration of 100-Gb/s wavelength division multiplexed transmission system and its paradigm-shift with digital coherent receivers.

systems.

In relation to the digital coherent receiver system, which will be a key technology for realizing a 100-Gb/s optical transmission system as mentioned above, the group including the authors has conducted research and development on digital signal processing algorithms and made detailed studies on their impact on the optical transmission system's characteristics. This paper first describes the historical and technological characteristics of digital coherent receivers and the challenges they face, followed by an overview of laser frequency offset compensation and carrier phase estimation, the most basic functions of the operation of the system, and the role of the respective functions. Then, this paper will explain the results of a real-time operation verification using a test receiver with these functions implemented.

2. Digital coherent receiver system and its history

A coherent receiver system[1)], which forms the foundation of a digital coherent system, is capable of achieving a reception sensitivity that is higher than the direct detection scheme conventionally used, and it was vigorously studied between the 1980s and the first half of the 1990s with the aim of extending the regeneration transmission distances of optical fiber communication systems. In this period, pioneering studies also began on the digital coherent receiver system, which is a variation of the coherent receiver system.[2)] However, as a result of the emergence of optical relay amplification technology and the dissemination of wavelength division multiplexing transmission technology, the motivation for employing coherent receivers for optical fiber communication systems disappeared for a time, and the R&D in this field dwindled for the next decade. Subsequently, however, the digital coherent receiver system returned to the limelight, and the factors in the background of this return include the following four points:

1) With a high-speed transmission system of 100 Gb/s, an insufficient receiver Optical Signal to Noise Ratio (OSNR) was a pressing problem for long-distance transmission and the improvement of OSNR tolerance brought about by coherent receivers came to be appealing again.
2) The strong waveform equalization function offered by the digital coherent receiver system came to be regarded as essential for addressing waveform distortion in the long-distance transmission of high-speed signals.
3) Along with the rapid progress of CMOS LSI technology, the digital signal processing capacity (number of gates and operating frequency) dramatically improved and the realization of a digital coherent receiver system for 100-Gb/s-class signals came to seem possible.
4) As bit rates became higher, addressing laser phase noise, which was one of the biggest obstacles to the realization of a coherent receiver system, became relatively easy.

With these factors in the background, some test results in relation to digital coherent receiver technology have been reported. However, the number of test reports on real-time operation with an actual digital coherent receiver prototyped is relatively small[3)-6)] and the majority of other reports are confined to so-called "offline tests" that employ a combination of burst waveform accumulation using a real-time oscilloscope and post-processing with software. For that reason, there are no studies or reports available that delve into the challenges of having real systems operate stably in reality, and there are still problems remaining before the technology can be put to practical use.

3. Characteristics of digital coherent receivers

An example of a basic functional block diagram of a digital coherent receiver is shown in

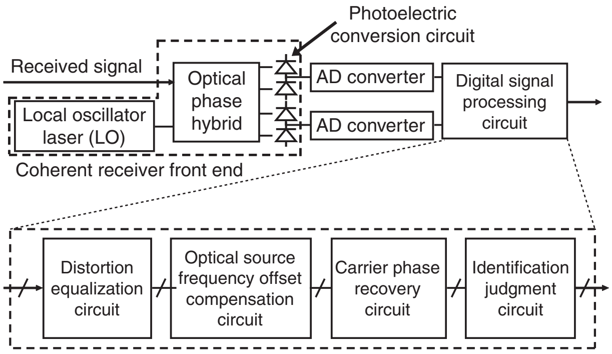


Figure 3
Example of basic functional block diagram of digital coherent receiver.

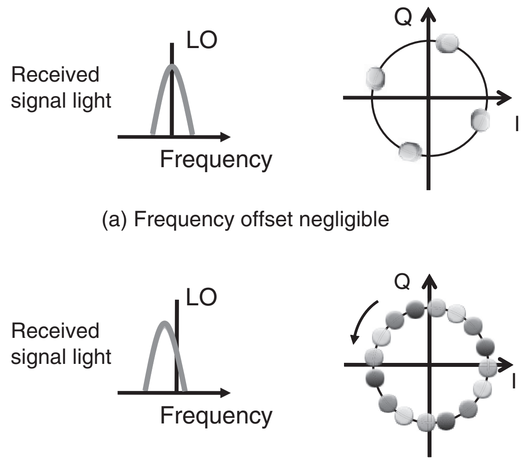


Figure 4
Impact of laser frequency offset: schematic diagram assuming QPSK system.

Figure 3. Compared with the conventional (non-digital) coherent receiver, the coherent optical receiver front end (consisting of a local oscillator laser [LO: Local Oscillator], optical hybrid,note 3) photoelectric conversion circuit, etc.) is mostly the same. The difference is that the output is A-D converted, and then subject to waveform processing by a digital signal processing circuit. This difference brings about the following specific advantages:

1) The implementation of a mechanism that synchronizes the frequency and phase of the transmission laser and LO with the received light as a digital signal processing function eliminates the need for an optical PLL, which is difficult to realize.
2) As a result, a laser for wavelength division multiplexing that is commonly available on the market can be applied as a free-running LO.
3) The digital signal processing circuit allows the realization of an advanced waveform distortion equalizer, which is difficult to realize with an analog circuit.
4) Flexible combination with various modulation schemes (multi-valued PSK [Phase Shift Keying] QAM [Quadrature Amplitude Modulation], etc.) or intra-wavelength channel multiplexing (polarized wave multiplexing, orthogonal frequency division multiplexing [OFDM], etc.) can be achieved by making only the minimum changes to the hardware architecture.

The following sections elaborate on the aforementioned 1), which is the most basic function in the realization of a real-time coherent receiver, by focusing on two circuits: a laser frequency offset compensation circuit and a carrier phase recovery circuit.

3.1 Laser frequency offset compensation

When a common laser for wavelength division multiplexing is used, a shift (offset) in the optical frequency may be generated within the range of the wavelength accuracy between the laser of the transmitter and the LO laser of the receiver. With lasers for wavelength division multiplexing commonly available on the market, this frequency offset may be up to several GHz.

The following explains the phenomenon that may arise when a laser frequency offset exists by using **Figure 4**, which takes a Quadrature Phase Shift Keying (QPSK)

note 3) Optical component that mixes a local oscillator laser and received light at two or more different phases for output.

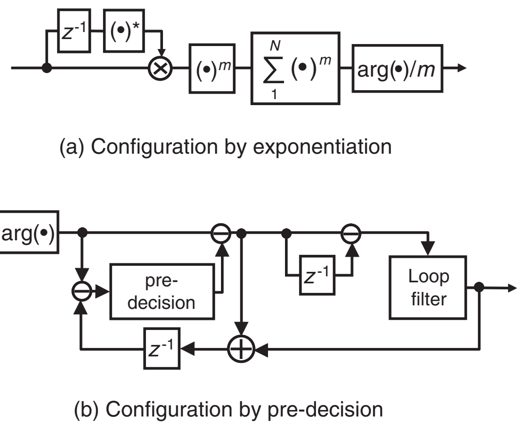


Figure 5
Functional block diagrams for laser frequency offset estimation circuit for mPSK signals.

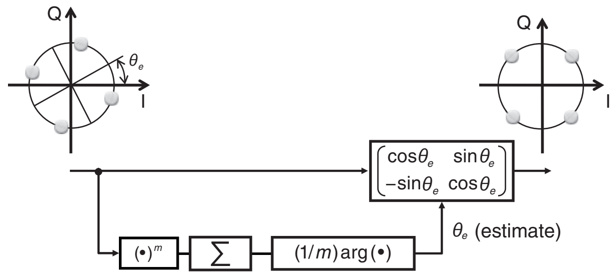


Figure 6
Functional block diagrams for carrier phase recovery circuit for mPSK signals.

modulation scheme[note 4)] as an example. When the laser frequency offset is sufficiently small [Figure 4 (a)], the signal constellation[note 5)] observed for a certain short period of time only presents static rotation caused by a phase shift. When the optical frequency offset is large [Figure 4 (b)], on the other hand, the constellation is rotated within the observation period because of the frequency offset and it is difficult to process and identify the signal as a QPSK signal without taking any measures.

To address this problem, a laser frequency offset estimation circuit for detecting the laser frequency offset becomes necessary first. As examples of laser frequency offset estimation circuits, two configurations applicable to multi-valued PSK modulation are shown in **Figure 5**. Figure 5 (a) shows a configuration in which a concept similar to carrier phase estimation for PSK signals, which will be described later, is used for removing the coded PSK signal and noise components from the complex electric field information received for extracting the laser frequency offset component.[3)] The configuration in Figure 5 (b) uses a method of removing the coded PSK component by subtracting the result of pre-decision of the signal, thereby further expanding the frequency offset estimation range.[6)]

Once a frequency offset estimate has been obtained using a circuit as described above, either of the following methods can be used to realize a frequency offset compensation circuit:

1) Feedback: the LO oscillation frequency is fine-tuned.
2) Feedforward: the constellation is reverse-rotated by an amount equivalent to the frequency offset in the digital circuit.

3.2 Carrier phase estimation

What remains after the frequency offset between the laser of the transmitter and the LO laser of the receiver has been compensated for is the phase difference between the lasers. The function to detect and correct this difference to prepare for identification judgment is the carrier phase estimation process.

As an example of a carrier phase recovery circuit, a sample configuration with exponentiation[7),8)] applicable to the PSK applied is shown in **Figure 6**. In this circuit, the complex electric field of an mPSK signal is raised to the power m to converge the code information into one point on the complex plane, which is used for deletion. In addition, equalization is performed among a certain number of symbols to reduce

note 4) Four-value phase modulation; a method in which two-bit information is associated with four optical phase states (45°, 135°, 225° and 315°) for transmission.

note 5) A representation on the complex plane of how the amplitude and phase of light are coded.

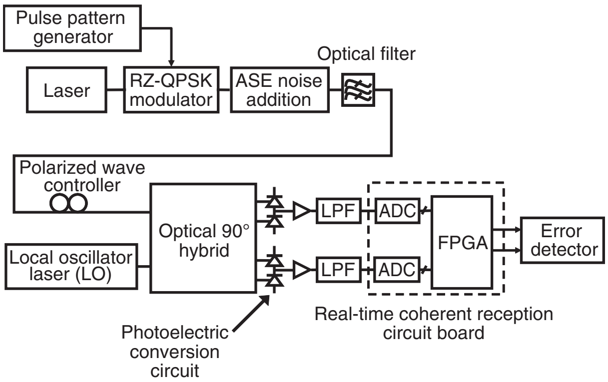


Figure 7
Experimental setup for real-time digital coherent reception of RZ-QPSK signal.

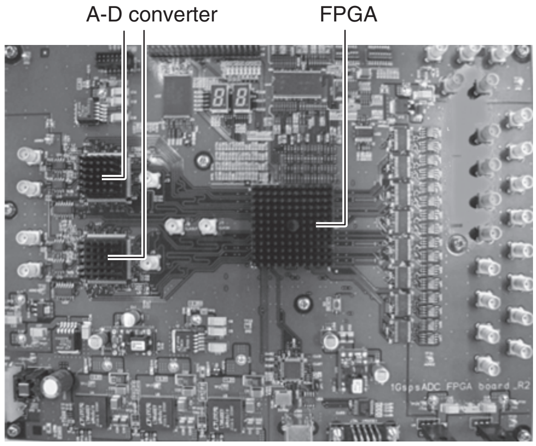


Figure 8
Real-time digital coherent reception circuit board.

the noise component, thereby calculating the carrier phase θ_e, which changes relatively slowly as compared with the noise. Once θ_e has been found, it can be used for rotating the constellation to eliminate the effect of the carrier phase, which allows decision by using certain thresholds.

4. Real-time digital coherent receiver testing

To verify the algorithms and circuits for digital coherent receivers as described above, an operating principle check by offline testing alone is not sufficient, and verification via real-time receiver testing is essential.

Accordingly, a test digital coherent receiver was fabricated, albeit with a low A-D conversion rate of 1 G samples/sec, and the basic characteristics were evaluated by real-time testing.

Note that, since the issues of laser frequency offset and carrier phase shift are more serious with a lower A-D conversion rate, the present evaluation results are rigorous rather than lenient as an evaluation of algorithms for high-speed operation.

The experimental setup is shown in **Figure 7**. In this test, a 1-Gb/s (500-Msymbols/sec) RZ-QPSK[note 6)] scheme was used as a modulation signal. As the lasers of the transmitter and receiver, variable-wavelength lasers of 300 kHz in laser line width were used to allow the laser frequency offset to be varied by finely adjusting the oscillation wavelength. ASE noise was added to the signal light to adjust the OSNR and the polarization was controlled with a polarization controller before injecting it into the coherent receiver. The coherent receiver is composed of an optical hybrid, LO, photoelectric conversion circuit, low-pass filter (350 MHz) and real-time coherent reception circuit board and the output was evaluated with an error detector. The real-time coherent reception test circuit board used for the test is shown in **Figure 8**. The outputs from two channels of the A-D converter of 1 G samples/sec were input into the FPGA for digital signal processing. As digital signal processing circuits, a laser frequency offset compensation circuit, carrier phase recovery circuit and decision circuit, which provide the most basic functional block, were implemented. As a laser frequency offset compensation circuit, a feedforward compensation method by either of the two types of offset estimation circuit shown

note 6) The amplitude envelope waveform of the individual QPSK code has been taken as a RZ (return to zero) pulse.

in Figures 5 (a) and (b) was used for comparing the two for evaluation. For the carrier, the exponentiation (QPSK, hence m = 4) mentioned above was used as a phase recovery circuit. Carrier phase estimation by exponentiation has a phase uncertainty of 360°/4 = 90° and any effect of noise may generate a burst error. To avoid this problem, a differential decoding function was provided for the decision circuit.

Figure 9 shows a sample result of extraction and visualization of the A-D converter output and the phase information immediately before decision. A comparison between Figure 9 (a) and (b) indicates that the implemented frequency offset compensation and carrier phase recovery circuit have eliminated the effect of the laser phase noise and frequency offset, and allowed detection of QPSK code four-value phase information.

Next, the bit error ratio was measured as a function of OSNR after setting the laser frequency offset at nearly 0 MHz (**Figure 10**). The OSNR is defined as the ratio of ASE noise optical power per 0.1 nm optical band to full signal optical power and the value may be negative. Measurements 1 and 2 in Figure 10 are the respective results obtained when the configurations in Figure 5 (a) and (b) were used as the laser frequency offset estimation circuit. The Figure first shows that, with either method, a favorable BER with not much floor can be achieved up to a BER of 10^{-12} (with offline testing, the number of bits measurable within a practical time period is limited and low BER characteristic check itself is difficult). A comparison of the obtained measurement results with the theoretical limit of the QPSK scheme indicates that the deviation is confined to only about 1 dB in terms of OSNR. To the best of the authors' knowledge, this result is the closest to the theoretical limit as the actually observed characteristic of a real-time digital coherent receiver reported so far.

Figure 11 shows the results of measuring laser frequency offset dependence with an OSNR of -2 dB, where the vertical axis shows the Q-factor deterioration calculated based on the BER. It has been confirmed that, with the frequency offset estimation method in Figure 5 (b) suggested by the authors' group (Measurement 2), almost twice as large a compensation range as with the conventional technology (Measurement 1)

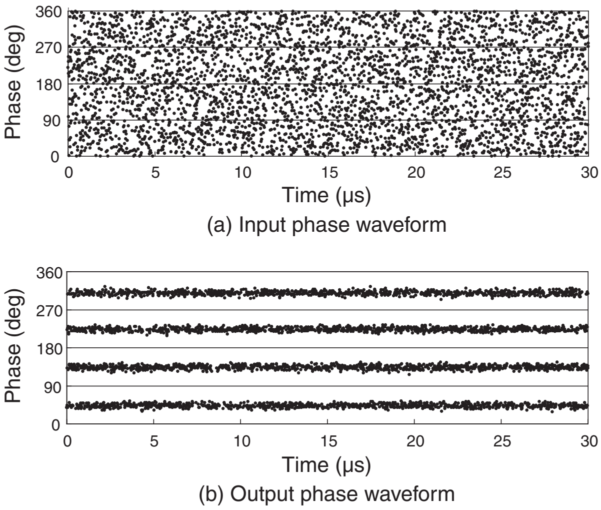


Figure 9
Input and output waveforms of the digital signal processing circuit (phase information only).

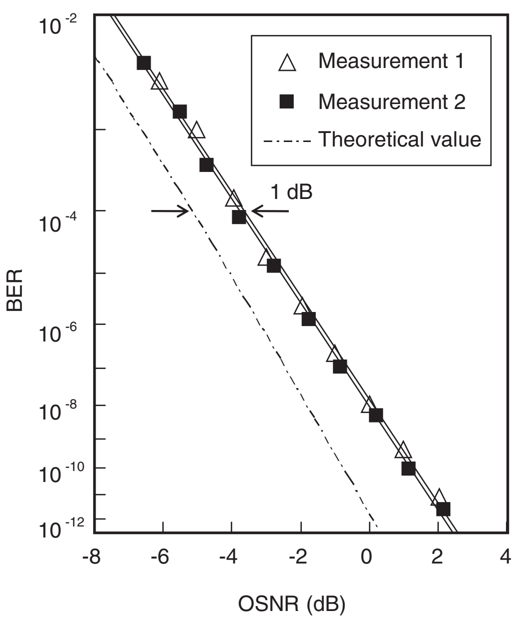


Figure 10
Measurement result of bit error ratio performance.

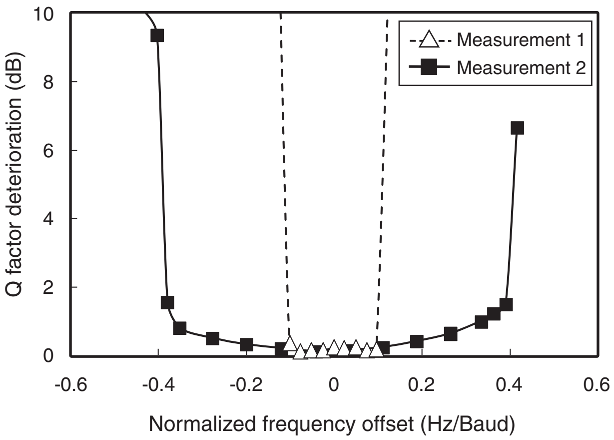


Figure 11
Measurement result of laser frequency offset tolerance (OSNR=-2 dB).

can be ensured. To convert the frequency offset range in terms of a 40- to 100-Gb/s QPSK signal receiver, the wavelength accuracy and stability offered by common semiconductor lasers for wavelength division multiplexing (frequency accuracy: +/-2.5 GHz) is sufficient. This result suggests that there is reasonable hope that the present basic algorithms can be used for practical applications.

5. Conclusion

To ascertain the capabilities of coherent receiver technology, which is prospective as an essential technology for optical transmission systems in the 100-Gb/s generation, and realize a stability that is adequate for real system operation, the most basic circuits in digital coherent receivers, including an optical frequency offset compensation circuit and carrier phase estimation circuit, were fabricated for evaluation in real-time testing. As a result, an excellent characteristic of a BER of only 1 dB away from the theoretical limit has been confirmed.

In the prototyping and testing done in this paper, the focus was placed on the basic functions that are sufficiently verifiable with a low signal bit rate. In the future, advanced functions unique to digital coherent receivers such as waveform distortion equalization and polarization control are scheduled for similar verification.

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