Development of Coherent Detection Method with Optical Phase-Locked Circuit

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The explosive growth of Internet traffic in recent years has necessitated the increase of the optical backbone capacity. Wavelength division multiplexing that handles large number of optical wavelengths is a standard technology used in realizing the capacity increase. However, since the increase in the traffic is expected to far exceed the bandwidth that can be accommodated by wavelength division multiplexing technology alone, coherent optical transmission technology capable of improving the efficiency of bandwidth utilization over conventional OOK (On/Off Keying) was developed. In coherent optical transmission, numerous optical signal states are created by applying phase or amplitude modulations to the optical carrier wave. Then, multibit digital data is associated with those signal states to enable multibit transmission using a single symbol. The use of 100Gb/s long-haul coherent optical transmission systems is already widespread, and they form the backbone of the large capacity trunk lines. Furthermore, 400Gb/s optical transmission systems are slated to appear on the market in the near future[1]. In coherent optical transmission systems, quality-monitoring equipment, which detects waveform deterioration due to accidental breakdown or component damage for quickly eliminating the fault, is indispensable. Currently such equipment is based on a high-speed digital signal processing system and requires 50GSample/s or greater ultrahigh-speed A/D converter and logic circuit resulting in the problem of large power consumption and high cost.

To solve the problem, OKI along with Alnair Labs Corporation, Nippon Telegraph and Telephone Corporation, The University of Tokyo and Tohoku University is participating in the 2015 “Research and Development of a Compact Optical Phase-Locked Circuit for Low Cost Reception and Monitoring of Optical Signals” collaborative research commissioned by the National Institute of Information and Communications Technology (NICT). This collaborative research is being conducted to develop a quality monitoring equipment using optical phase-locked technology, which is a promising detection and monitoring method based on analog processing for low cost optical coherent transmission. OKI has been entrusted with the system design and operation verification of the optical phase-locked circuit.

In the commissioned research, an optical phase-locked technology is being developed aimed at the realization of a quality monitoring equipment usable with a 25Gbaud-QPSK (Quaternary Phase Shift Keying) found standard in current 100Gb/s backbones. This article introduces OKI’s effort and results in the commissioned research.

Overview and Issues of Optical Phase-Locked Technology

(1) Optical Phase-Locked Technology Overview

Optical phase-locked technology reproduces the carrier wave from the received optical phase-modulated signal. It has been vigorously researched since the 1980's as a core technology for demodulating the transmitted digital code. However, long-term stable operation is difficult, and it has not been technically established at a practical level. **Figure 1** shows the demodulation of BPSK (Binary Phase Shift Keying), which is a representative example of a phase-modulated signal. Data bits 0 and 1 are superimposed on the phase of the carrier with constant amplitude as phase inversions of 0 and π, respectively. When light waves having the same frequency, called local oscillation light, is superimposed in the same phase, the phase-inverted portions are converted into intensity changes. As a result, portions with the same phase are associated with 1, portions with opposite phases are associated with 0, and data detection becomes possible. Therefore, an optical phase-locked circuit that generates highly accurate local oscillation light with the same frequency and phase from the BPSK is required.

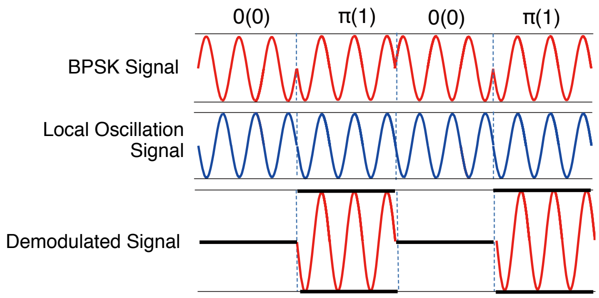


Figure 1. Detection Example of BPSK

Figure 2 shows the basic configuration of an optical phase-locked circuit for demodulating an optical phase-modulated signal. The received optical phase-modulated signal is multiplexed with the output from the local oscillation light source by the 90° optical hybrid. The resulting signal enters the photoelectric converters where it is converted to an I (In-phase) component electric signal, which is in phase with the carrier wave, and Q (Quadrature-phase) component electric signal, which is orthogonal to the carrier wave. The exponentiation circuit performs appropriate multiplication processing on these two components, whereby the phase error between the carrier wave of the optical phase-modulated signal and the local oscillation signal is extracted. Then, the phase error signal is smoothed using a low pass filter before being fed back to the local oscillation light source where control is performed such that the phase error eventually becomes zero.

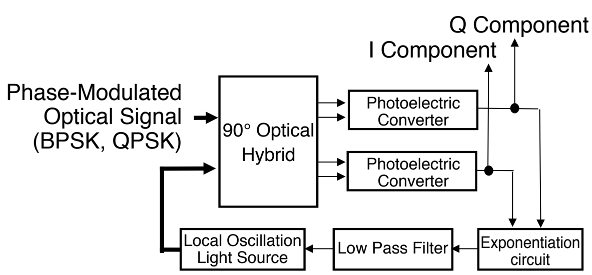
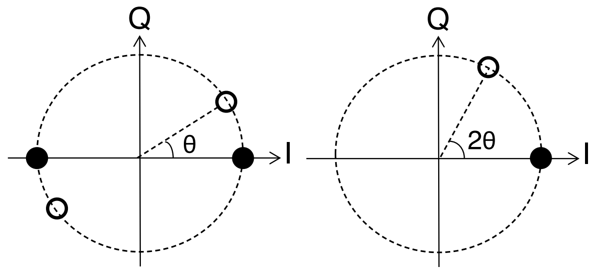


Figure 2. Basic Configuration of Optical Phase-Locked Circuit

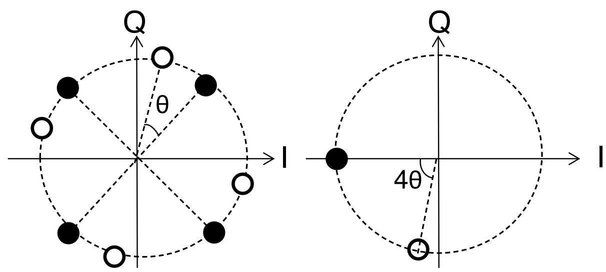
The exponentiation circuit in the configuration serves an important function, and that function is described below. **Figure 3** depicts the signal arrangement of BPSK. The horizontal and vertical axes are the I and Q components of the signal, respectively. The black dots in **Figure 3 (a)** represent data points that are phase-locked with the local oscillation light source. In the case of BPSK, there is no value in the Q axis direction, a component appears on the I axis, and the I coordinate values of the black dots located at phases 0 and π correspond to 0 and 1 data, respectively. If a phase error θ exists between the input optical phase-modulated signal and the local oscillation light source, it corresponds to the position indicated by the white dot in the figure. Although the difference between the black and white dots is the phase error, there are two data positions separated by a phase difference π. Thus, there are two possible phase differences, θ and θ+π, and they are indistinguishable as is.

To resolve the problem, an exponentiation circuit is utilized. The exponentiation circuit has a function corresponding to the exponentiation of complex numbers. For BPSK, square calculation is performed. Since the calculation doubles the phase angle, as shown in **Figure 3 (b)**, the signal synchronized with the local oscillation light source becomes a single point (black dot), and the phase-modulated signal also overlaps into a single point (white dot). This way, there is one phase difference, and that phase difference is twice the original phase error. In this manner, the phase difference between the carrier wave of the input signal and the local oscillation light source can be detected. Phase lock can be achieved by performing feedback control to bring the error component down to zero. In case of QPSK, there are four states separated by a phase difference of exactly π/2 as shown in the signal arrangement of **Figure 4 (a)**. Black dots in the figure represent data points that are phase-locked with the local oscillation light source. If there is a phase error θ between the input optical phase-modulated signal and the local oscillation light source, it corresponds to the positions indicated by the white dots. For QPSK, the exponentiation circuit performs fourth power calculation, which quadruples the phase angles. This overlaps the synchronized signal points into a single black dot and input phase-modulated signal into a single white dot as shown in **Figure 4 (b)**. At this time, the phase error is 4θ. **Figure 5** shows a calculation configuration example of an actual exponentiation circuit. According to this calculation processing, the data portion is eventually canceled out, and the 4θ component, which is four times the phase error, is extracted. Feedback control is performed using this component as an error signal, and by bringing down the error signal to zero, a local oscillation signal locked with the optical phase-modulated signal is obtained.



(a) Signal Arrangement (b) Phase Error after Exponentiation

Figure 3. BPSK Signal Arrangement



(a) Signal Arrangement (b) Phase Error after Exponentiation

Figure 4. QPSK Signal Arrangement

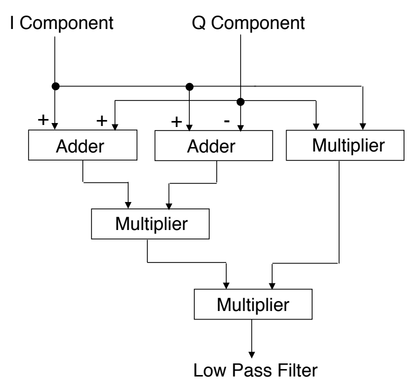


Figure 5. Calculation Required for Phase Error Extraction in QPSK

(2) Optical Phase-Locked Technology Issues

In order to realize the procedure described in the previous section, the following two technical issues must be resolved.

a) Technical Issue 1

First is the technology to realize an exponentiation circuit capable of handling symbol rates that are several tens of Gbaud. Since symbol rates of optical phase-modulated signals in general are several tens of Gbaud, the I and Q component bands exceed the operational limit of electronic circuits, and direct multiplication processing is difficult. In the 80km transmission test of a 10Gbaud-QPSK performed by the authors, the multiplication/addition was accomplished with digital processing using FPGA (Field Programmable Gate Array)[2)]. However, in the demodulation of 25Gbaud-QPSK where symbol rate is more than double, feedback delay becomes obvious due to the increased processing time of the input/output and digital calculations. There was a possibility this would degrade rather than improve performance for high symbol rates, which are sensitive to phase fluctuations.

b) Technical Issue 2

The second technology is shortening the delay time of the feedback system from the exponentiation circuit to the 90° optical hybrid. Unlike the RF (Radio Frequency) oscillator represented by the crystal oscillator, the laser, which is the local oscillation light source, has extremely poor coherence and large frequency instability (about 10 to 1000 times that of the high precision high frequency oscillator per second). Furthermore, when handling a high carrier wave frequency such as a light wave (for example, 10 to 200,000 times greater compared with radio waves of mobile phones), the phase variation caused by disturbances or the like becomes relatively larger than with conventional electric signals. Thus, in order to ensure robust operation, remarkably higher speed operation is required compared with phase-locked circuits in the electrical domain. To guarantee long-term high-performance operation, it is necessary to configure the feedback loop as small as possible using integration technology and minimize the time required for feedback. As a result, resistance to phase fluctuation inherent in the signal light/local oscillation light source is improved, and long-term stability during optical phase-lock is remarkably improved. At the same time, the size of the entire optical phase-lock system can be significantly reduced, and practicality can be greatly improved even when applied to sensor/measurement fields.

Development and Experimental Results of Optical Phase-Locked Circuit for Optical QPSK Demodulation

In the commissioned research, the following solutions are being considered to resolve the two aforementioned issues. For technical issue 1, the authors proposed signal decimation using a track & hold circuit to sample the I and Q components at a sufficiently low speed (1/250 of the symbol rate) and expanding the bit length of the decimated portion to the sampling cycle. This process corresponds to apparently lowering the symbol rate and makes it possible to decrease the bandwidth, so that processing can be sufficiently performed with commercially available analog electronic circuits. In addition, multiplication and addition in the exponentiation circuit can be performed through analog processing, thereby achieving faster calculation compared with the digital calculation described before. This is also considered effective in terms of reducing the delay of the feedback circuit. For a fundamental solution to technical issue 2, Nippon Telegraph and Telephone Corporation and The University of Tokyo will develop a device using optoelectronic integration technology based on silicon photonics, which will then be used to produce an ultra-compact optical phase-locked circuit for the project as a whole. To solve technical issue 2, methods are currently being studied for the optoelectronic integration of optical and electrical components. In 2019, the last year of the commissioned research, a final integration evaluation experiment together with the method proposed by the authors is planned.

Initial prototyping of a system incorporating the solution relating to technical issue 1 proposed by the authors was performed, and the results of the basic operation verification are described below. In the demonstration experiment, evaluation of the demodulation characteristics before and after an 80km transmission of 25Gbaud-QPSK shows the effectiveness of the proposed method. **Figure 6** shows the demodulated signal's symbol error rate before and after the transmission, and **Figure 7** shows the waveforms of the I and Q components at that time. Performance was good for both channels and was error free ($<10^{-9}$ @ -25dBm). As a result, the effectiveness of the proposed method was verified. For the details of the 80km 25Gbaud-QPSK transmission experiment with the optical phase-locked circuit, refer to Reference 3.

The first prototype was configured with the combination of low cost commercial products. From the results of this primary evaluation, the system fully demonstrated its usefulness as a low-cost quality monitor that can be used in short-distance networks (for example, supercomputer networks and data center networks) where waveform deterioration is presently not apparent. Future work will include verifying the operation and usefulness of the system for transmission speeds and wide range of the optical frequency band expected in the access systems five to ten years from now and expanding the usable fields of the system. When the technology is ultimately completed, it will be possible to constantly and easily monitor the quality of high bit rate optical phase-modulated signals at low cost, thus greatly contribute to the safe operation of optical communication networks.

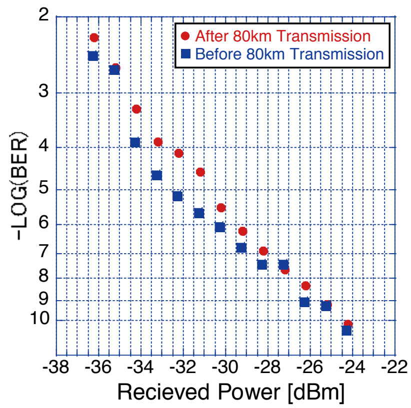
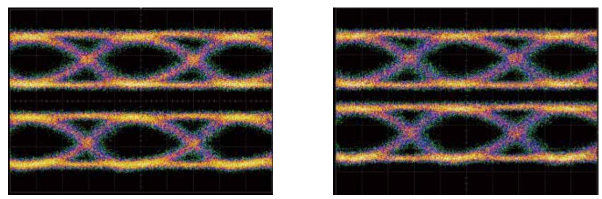


Figure 6. Symbol Error Rate of 25Gbaud-QPSK



(a) Before 80km Transmission (b) After 80km Transmission

Figure 7. Eye Pattern of Demodulated Waveform

Conclusion

This article outlined the optical phase-locked technology undergoing development based on the "Research and Development of a Compact Optical Phase-Locked Circuit for Low Cost Reception and Monitoring of Optical Signals" commissioned by NICT. It also presented the results of an experimental evaluation conducted with an 80km 25Gbaud-QPSK signal transmission. Optical phase-locked technology is important not only in communication but also in various sensing fields such as fiber optic and laser doppler sensors, which are increasingly important in recent years as IoT (Internet of Things) equipment becomes popular. OKI will continue to develop the technology with light wave sensing applications in mind.

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TIPS

【Glossary】

symbol rate
Digital data that can be transmitted with one modulation is called a symbol. If 2-bit information can be transmitted with one modulation, there will be four kinds of symbols. The transmission rate per second of this symbol unit is called a symbol rate (baud).

coherence
It is one of the properties of waves and represents the degree of phase alignment, that is, the ease of interference (the sharpness of interference fringes). The higher the coherence, the higher the phase alignment.

track & hold circuit
A circuit that samples the value of an analog signal at a given time and converts it into a 0th-order hold waveform by holding this value for a certain time period using the integral action of the capacitor.

OOK (On/Off Keying)
A modulation scheme for superimposing data bits on the amplitude of the carrier wave as a change in intensity.

BPSK (Binary Phase Shift Keying),
QPSK (Quaternary Phase Shift Keying)
A modulation scheme that superimposes data bits on the carrier wave phase as phase inversion. It is a typical coherent modulation scheme.