3-7 Highly Efficient Optical Communication Technologies

– Multi-level Optical Transmission and Ultra-high Density Optical Signal Processing –

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Highly efficient optical communication technologies are becoming important since the conventional strategies, such as denser wavelength multiplexing or higher time-domain multiplexing, are approaching their physical limits. Power-efficiency and volume-efficiency are additional important demands required in optical communications. In this paper, we show our recent development in high-efficient optical communications such as multi-level transmission technologies and high-density optical signal processing performed in a scale smaller than the diffraction limit of light.

Keywords
Highly efficient optical communication, Multi-level, Synchronous detection, Nanophotonics

1 Introduction

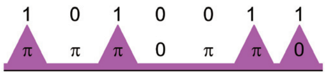
In response to expanding needs in information transmission, conventional optical communication technologies have seen increased bit rates per wavelength channel—to 2.5 Gb/s, 10 Gb/s, and 40 Gb/s—in addition to increases in the extent of wavelength multiplexing[1]. However, with increasing bit rates, waveform distortion due to dispersion is becoming a serious problem. The extent of multiplexing is also limited by the amplification band of the repeater amplifiers, such that two or more optical amplifiers with different amplification bands must be used in parallel. This requirement causes a number of problems, including increased power consumption in the repeater system. In addition, another significant problem is seen in the ultimate implementation of functionality in the optical domain, as with an optical data router. However, the diffraction limit of light (approximately 1 μm in communication wavelengths, which is approximately 100 times the line width of a VLSI circuit) represents a serious barrier in overall system integration, and many are hoping to see a breakthrough in this area. In short, demand is now high for the development of optical technologies that will facilitate a fundamental, widespread improvement in efficiency (e.g., in the efficiency of frequency use, energy use, and size). In light of these circumstances, this article describes the latest technological movements in optical signal processing aimed at achieving high efficiency. In particular, we will focus on multi-level transmission technology to enhance optical transmission capacity (Section **2**) and high-density optical signal processing technology on scales smaller than the diffraction limit of light, based on near-field optical interactions (Section **3**).

2 Time-domain high-efficiency optical signal processing technology (multi-level transmission method)

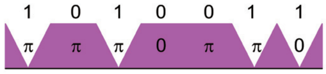
The multi-level transmission method has generated high expectations as a means of highly efficient optical transmission, with the potential to increase the capacity of information transmission by a factor of two to four or more[2]-[8]. Optical fiber communication is an extremely underdeveloped technology in terms of frequency use relative to wireless communication, which is already reaching the Shannon limit. Thus, optical communication presents the possibility of significant further development, including improved efficiency in information transmission and signal-processing technologies. Many methods of multi-level optical modulation have been reported to date. One example is seen in ASK-DPSK (APSK)[2], which combines Amplitude Shift Keying (ASK) and Differential Phase Shift Keying (DPSK); another method is known as Differential Quadrature Phase Shift Keying (DQPSK)[3], which uses the optical phase only. However, the ASK-DPSK method, which combines optical phase modulation and optical intensity modulation, presents the problem of waveform distortion caused by intermodulation in optical phase modulation (PM) caused by the optical amplitude modulation (AM) component. On the other hand, the DQPSK method requires a signal encoder entailing complicated operations in the electrical signal stage[3], which causes problems in realizing high-speed transmission of 40 Gb/s or greater. In addition, Differential Phase Shift Keying for multi-level transmission of 8 PSK or more is difficult for reasons similar to those limiting corresponding transmission in wireless communication. To the best of our knowledge, any established method for stable real-time multi-level optical phase synchronous modulation/demodulation with phase noise tolerance has not been reported. We have proposed the inverse optical pulse hybrid modulation method, which superposes optical phase modulation on inverse optical pulse signals, in a multi-level transmission system with low intermodulation. This section reports on the satisfactory intermodulation suppression offered by this method. Here we also discuss the Pilot Carrier aided self-homodyne detection method, which features superior phase noise resistance and stability. Overall, this method is aimed at the realization of ultra-high-speed multi-level transmission.

2.1 Inverse optical pulse hybrid modulation method[5]

Figure 1 shows a timing chart for the proposed inverse optical pulse hybrid modulation method. Introducing pulsed light into an inverse RZ modulator turns the “1” code in the data signal for optical amplitude modulation (“1010011” in Fig. 1) into a dip (dark optical pulse) and the “0” code into a high level, converting the input light into inverse RZ optical pulses with a duty ratio of 50 percent or greater (Fig. 1 (b)). The inverse RZ optical pulses are then further superposed with phase modulation (“$\pi\pi\pi0\pi\pi0$” in Fig. 1). The conventional optical phase/amplitude hybrid modulation method (Fig. 1 (a)) purposely degrades the extinction ratio in order to superpose phase modulation on low-level optical pulses corresponding to the “0” code. Thus, delicate adjustment of the extinction ratio is required to balance the quality of the two signal components—optical phase and optical amplitude—in addition to accurate matching

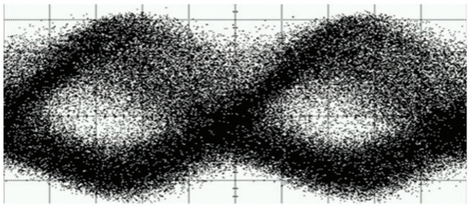


(a) Conventional scheme : Large AM→PM inter-modulation

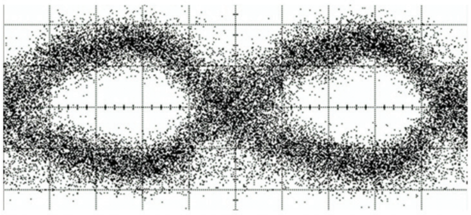


(b) Proposed scheme : Reduced AM→PM inter-modulation

Fig. 1 Timing chart for inverse optical pulse hybrid modulation method of the time slots for amplitude modulation and phase modulation. On the other hand, inverse RZ optical pulses feature a duty ratio of 50 percent or more, such that synchronization of the time slots for phase modulation and amplitude modulation is not necessarily required (Fig. 1 (b)). The receiver unit divides the optical signal into two and sends the split signals into the optical amplitude detection unit and the optical phase detection unit. These units separately demodulate the signal. Figure 2 shows the waveforms of the received signal with the proposed method (a) and with the conventional method (b), for 20-Gb/s optical phase/amplitude hybrid modulation (2 bits/symbol: doubled information transmission efficiency; 20 ps/div). The figure confirms that the proposed method can significantly reduce the waveform distortion caused by intermodulation from the optical amplitude component to the optical phase modulation data component. We have also confirmed that combining DQPSK modulation and the inverse RZ optical pulses effectively suppresses the intermodulation caused by the amplitude modulation for 30-Gb/s, 3-bits/symbol (tripled information transmission efficiency) transmission and produces error-free characteristics (i.e., with a bit error rate (BER) less than10^{-9})[5].



(a)従来方式



(b)提案方式

Fig.2 Waveforms observed in phase detection for 20-Gb/s optical phase/amplitude hybrid modulation

2.2 Pilot Carrier multi-level optical phase synchronous detection method[6][7]

Figure 3 shows a conceptual illustration of the proposed multi-level optical phase synchronous detection method for 2-bits/symbol transmission (or QPSK, for Quadri-Phase Shift Keying). Under the conventional optical phase synchronous detection method, the transmitter leaves a slight component from the carrier, using an incomplete phase modulation, and the receiver traces this slight residual component of the carrier using an optical phase-locked loop (or “optical PLL”). Thus, extremely stringent phase noise performance is required, and it is therefore difficult to obtain stable optical phase synchronous detection[8]. For this reason, we allowed transmitter input light (linearly polarized at 45 degrees) into a phase modulator that only modulates the phase of the light in the TM direction. In this manner, the multi-level phase modulated optical signal (TM) and unmodulated CW light (TE), which acts as a Pilot Carrier, are generated together. We constructed the receiver with a module consisting of an LN waveguide with an integrated polarized beam splitter, half-wave plate, optical phase adjuster, and multiplexer (Fig. 4). The polarized beam splitter performs homodyne detection by rotating the polarization of only the Pilot-Carrier component 90 degrees. Although the receiving system requires polarization control, the phase control system needs only to adjust the relative phase in a narrow band that includes the polarization dispersion fluctuation. As a result, this method significantly reduces the requirements with respect to the spectral line width of the light source relative to conventional optical PLL, which uses a local oscillator as a light source. Compared to the Differential Phase Shift Keying method, this approach does not make use of the previous bit in operation. This method therefore does not require an encoding/decoding unit,

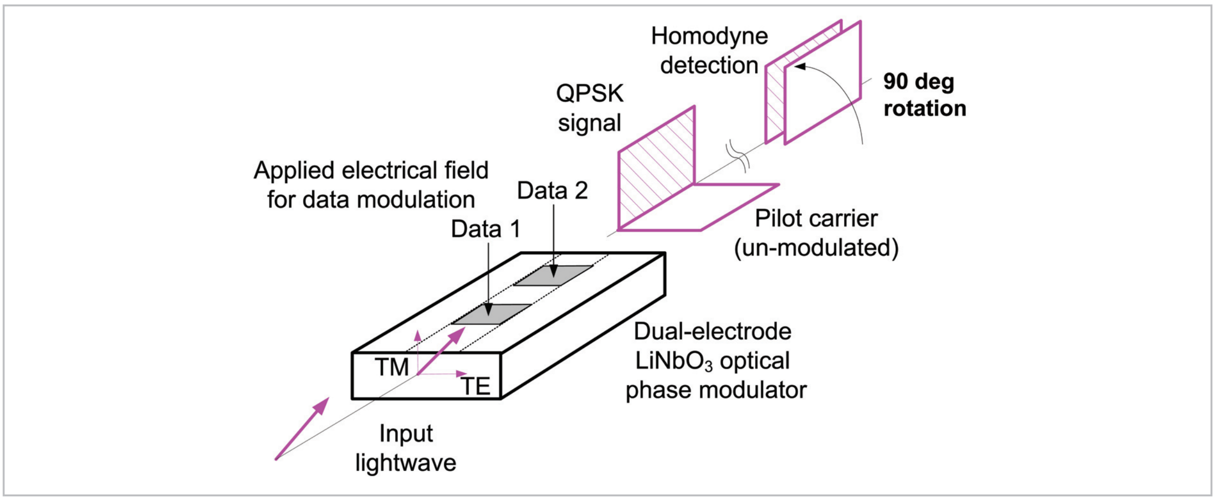


Fig.3 Pilot Carrier self-homodyne detection method

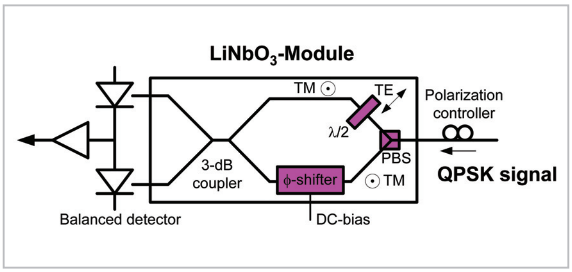


Fig.4 LN integration module

which would involve complicated processes within the electronic circuits, in turn causing problems in ultra-high-speed transmission. Balanced homodyne detection in the receiver is also expected to suppress intermodulation caused by the amplitude modulation component and amplitude noise.

Figure 5 shows the RF frequency characteristics of the Common Mode Rejection Ratio (CMRR) for synchronous homodyne detection of the prototype LN integration module. When the frequencies of the received signal were 1 GHz and 10 GHz, we obtained superior CMRR of 30 dB and 15 dB, respectively. Figure 6 shows the dependence of receiver sensitivity on spectral line width (full width at half maximum) for the light source, as defined by an error rate of 10^{-9} at the time of 20-Gb/s (2 bits/symbol) QPSK synchronous homodyne detection. In past experimental reports on QPSK phase synchronous detection based on a local oscillator in the receiver system[4][8], the spectral line width of the light source is on the order of several hundred kHz in all cases (to the left of the dotted line in the figure). However, the proposed method only slightly degrades receiver sensitivity and produces an extremely fine receiver waveform for a light source with a line width of 30 MHz (indicated as B in the figure), even compared with a case in which line width is 300 kHz (indicated as A in the figure). This is because the proposed method uses the LN module and performs autonomous homodyne detection of the Pilot Carrier, which carries a phase noise identical to that of the signal component. This procedure cancels out the phase noise.

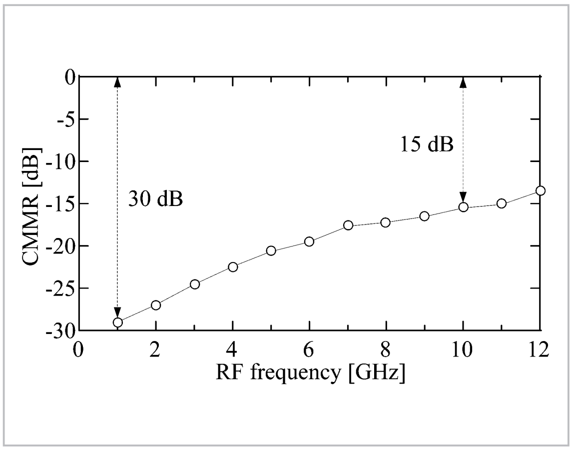


Fig.5 RF frequency characteristics of the Common Mode Rejection Ratio in synchronous detection

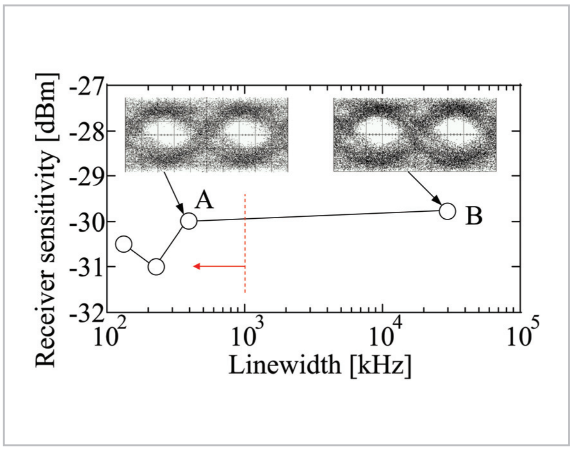


Fig.6 *Dependence of receiver sensitivity on spectral line width in QPSK synchronous homodyne detection*

3 Highly efficient signal processing technology in the spatial domain (ultra-high-density optical signal processing)

In addition to increased efficiency in the time domain as discussed in Section **2**, another important problem remains for next-generation optical systems in increasing efficiency in the spatial domain. The diffraction limit of light (approximately 1 μm in the communication wavelength) is seriously restricting system integration. To overcome such physical limitation of conventional optical technologies, we have focused on nanophotonics, based on near-field optical interactions, which is free from the diffraction of light. We investigated basic problems in high-efficiency optical signal processing in the spatial domain (i.e., high-density optical signal processing) regarding the functionalities required, such as optical table lookup processing in optical data routers and optical CDM, based on the physical principles that are uniquely available in nanophotonics.

3.1 Local near-field optical interaction and global signal processing

Here we take the optical table lookup processing required in an optical data router as an example. Optical table lookup is a matching operation between the destination address of the input packet and the routing table in the router. Let us consider the basics of its optical implementations based on near-field optical interactions[9]. We have found that a table lookup or a matching operation requires the following two basic mechanisms.

(1) Input data items are generally constructed with two or more bits, and we must obtain evaluation results for all of these bits. In other words, it is not sufficient to clarify matching or mismatching for each bit; therefore it is necessary to provide a mechanism of global evaluation among the entirety of the bits (i.e., global summation).

(2) Input data should be compared with as many data entries in the routing table as possible. In other words, a data broadcast mechanism is required. Even if the basic processes described in (1) may be integrated in a nano-scale, the entire system—containing many of these integrated modules—must work as a massively parallel processing system.

Here, propagating light is, in fact, extremely suitable for such global functionalities as are described in (1) and (2) above, and has played an important role in conventional optical signal processing. In other words, the propagating character of this conventional lightwave naturally matches the global functionalities by means of lenses or optical waveguides. However, the diffraction of light poses a serious problem; the size of the entire system generally becomes impractically large. On the other hand, one of the ultimate characteristics of optical near-fields is its physical locality; it does not propagate. Therefore, one of the basic problems in the optical signal processing in the nanometer-scale is to achieve “global functionality” based on “physically local” mechanisms. Thus, we will show an example of an architecture that takes advantage of the two characteristics of optical near-fields: (1) the resonance energy transfer between closely separated quantum dots, and (2) the fact that this energy transfer is forbidden in conventional propagating light.

3.2 Global summation of data

We can transfer signals (excitons) to a particular quantum dot using the near-field optical interaction between quantum dots. For example, there is a resonance energy level between a quantum dot of size a and a quantum dot of size $\sqrt{2}a$. The signal (exciton) generated in the smaller dot can move to the larger dot through this resonance level[10]. Thus, if the system features a structure in which the smaller dots surround the larger dots, as shown in Fig. 7, the excitons in the smaller dots move to the larger dots. In this manner, the global summation operation Σx_i is implemented in nano-scale by an appropriate configuration of the quantum dots of appropriate sizes.

Here, the details of the exciton transfer mechanism are as follows. As an example, between quantum dot QD$_A$ of size a and quantum dot QD$_B$ of size $\sqrt{2}a$, resonance energy levels ((1,1,1) for QD$_A$ and (2,1,1) for QD$_B$) are present, and the exciton of QD$_A$ moves to QD$_B$ through this level and transitions to the lower level, (1,1,1), of QD$_B$. The energy dissipation involved in this process is attributed only to the sublevel relaxation in QD$_B$; Therefore this mechanism is also significantly energy-efficient compared both to electric VLSI circuits and to existing optical technologies. The lower level of QD$_B$ is used for the output signal. Here, when the lower level of QD$_B$ is occupied by a signal from other dots, energy transition is forbidden due to Pauli's exclusion principle. In this case, the so-called optical nutation occurs meaning that the exciton goes back and forth between QD$_A$ and the upper level of QD$_B$, enabling the exciton to move to the lower level of QD$_B$ in the end. Such partially bidirectional signal transition also contributes to the global summation. Figure 7 presents an experiment based on this principle using CuCl quantum dots. The figure indicates the output signal (384 nm) for a combination of input light at three different frequencies (381.3 nm, 376 nm, and 325 nm). The figure confirms an output signal level in accordance with the number of input signals and shows that the system is integrated on a scale smaller than the diffraction limit[11].

3.3 Data broadcasting

Input data need to be provided for many data entries in the lookup table. If individual data items require individual waveguides, the physical volume necessary for the wiring will form a serious interconnection bottleneck. Here, by taking note of the broadcast structure, we can make use of the fact that the signal-transfer mechanism using optical near-

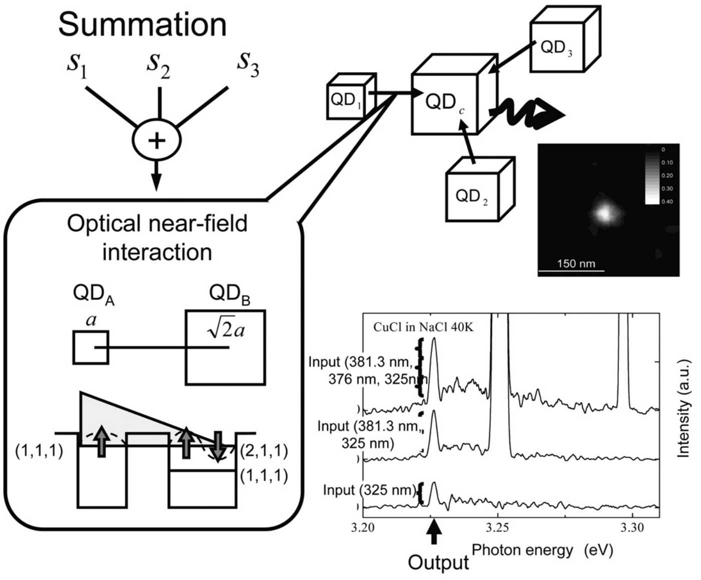


Fig.7 Global summation of data based on optical near-field interactions

field interactions is forbidden in propagating light. For example, propagating light cannot excite the upper level (2,1,1) of QD_B (forbidden dipole). Thus, if we select light at a frequency that does not influence operation within the device, we can simultaneously provide data to two or more independent circuit blocks. In other words, if the system is designed to use light energy without overlap at energy level Ω_{int} (relating to the internal operation) and energy levels Ω_{in} and Ω_{out} (relating to input and output), multiple bits can be broadcast by using propagating light at different frequencies. Figure 8 shows an example of an experiment based on this principle using the same CuCl quantum dots described earlier. The figure shows the multiple optical switches (indicated by the closed square, the closed circle, and the closed diamond) in the sample are operated simultaneously with lights which are uniformly irradiated within the entire system; meaning that individual addressing is not required for each of the switches. In other words, the principle of broadcast interconnects was confirmed[12].

The summation and broadcast processes described above are the basic fundamental processes for optical table lookup operations. However, it covers a wide range of computations since the summation and broadcast leads to the so-called memory-based architecture, which covers a variety of signal processing applications. In their practical realization, stable operation at room temperature and operation in the communication wavelength band will be important. In this respect, we have demonstrated the operation of these principles based on semiconductor quantum dots[13] and will continue to pursue further development in this area.

4 Future developments

For the 100-Gb Ethernet, planned for introduction around 2010, there is some concern that current optical amplifier bandwidths will prove insufficient. In this context much is expected of the highly efficient multi-level optical transmission method, as a decisive technology that can both increase transmission capacity and suppress power consumption within a network system. In addition, dynamically changing traffic must be accommodated efficiently while maintaining the desired signal quality. Thus, we are eager to make progress on this highly efficient adaptive modulation method, which will enable adaptive configuration of information transfer efficiency (at 2 to 4 bits/symbol or more), when applied in combination with the highly effi-

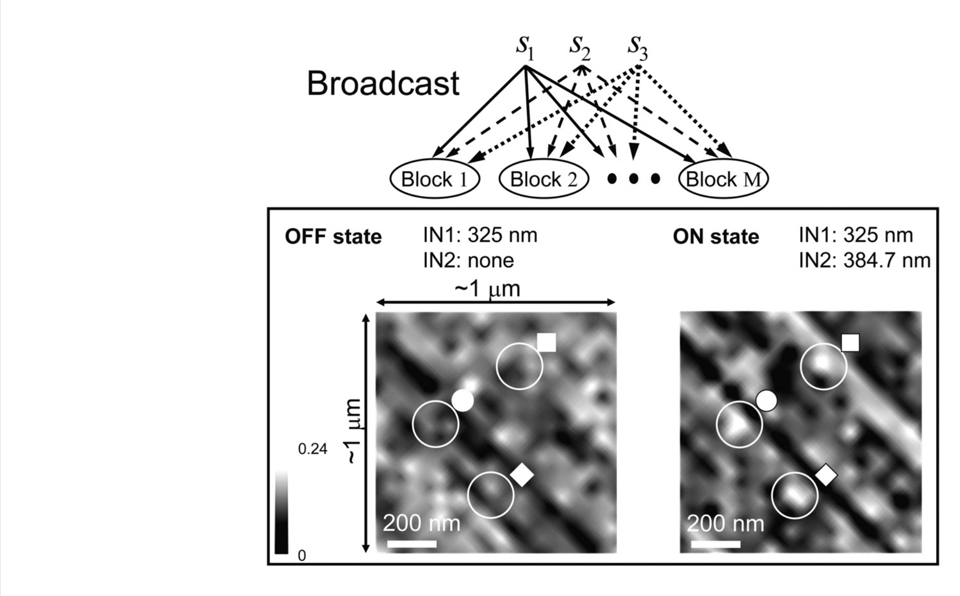


Fig.8 Broadcast of data based on the near-field optical interaction

cient optical modulator NICT has been developing to date (See Article **3-6**,) as well as with private-sector technologies such as high-performance FEC. The nanophotonics technology constituting the basics of ultra-high-density optical signal processing can also be fused with advanced practical technologies such as those relating to quantum dots and metal nanostructures. The relevant research and development is rapidly beginning worldwide in key areas of optical technology. Aiming at early acquisition of next-generation key technologies, we hope to continue to promote research and development as we solidify the basic technologies involved.

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