3-6 Advanced Optical Modulators for Next-generation Photonic Networks

KAWANISHI Tetsuya and SAKAMOTO Takahide

This article describes recent research activities using an NICT novel optical device, the optical frequency-shift-keying (FSK) modulator, which can provide high-speed control of optical frequency, phase and amplitude. The FSK modulator can generate various types of high-speed optical signals, precisely. We show a couple of examples of recent results on applications of the FSK modulator for next-generation optical communications systems, such as, optical FSK label processing, tunable optical buffer techniques, high-speed differential quadrature-phase-shift-keying (DQPSK) signal generation for 100 GbE and continuous-phase FSK signal generation for dense wavelength-domain-multiplexing.

Keywords
Optical modulator, Optical buffer, Optical label, Phase, Frequency

1 Introduction

Today we are witnessing the spread of high-speed Internet access services such as ADSL and FTTH, with a variety of services provided via continuous connection even in homes. Some of these services require large transmission capacity, as in the expanding range of audio and video network applications. In terms of audio applications, manufacturers have shifted emphasis in their main portable audio equipment products toward devices based on MP3 technology and have already begun a number of network music distribution services. On the other hand, while audio services on the Internet offer quality equivalent to that of audio equipment, video distribution urgently requires further advances in network performance. Specifically, innovative optical devices must be developed to enable digital high-definition image distribution. Optical communication technology is already used in many fields, from international communications to home FTTH. With these services, optical signals are mainly used to implement point-to-point transmission. When complicated processing is required, optical signals are generally converted into electrical signals for processing in electrical circuits. Processing in the electric circuit forms a bottleneck in this case, and various studies are underway to address this problem. As is widely known, light has a dual wave/particle nature. Most existing optical communications systems do not take advantage of this nature and use only two states of light: on or off. Here we will discuss the fundamentals of an ultra-high-density optical technology that takes full advantage of the wave properties of light, increases transmission capacity, and provides for a number of new functions required for optical signal processing. We also describe a unique device developed by NICT enabling free use of all three elements of a wave: intensity, phase, and frequency (or wavelength). We also describe an ultra-high-speed transmission system and a packet system based on this device.

2 Fundamental technology for ultra-high-density optical communications

In the field of wireless technologies, systems that take full advantage of the wave nature of radio communications are in wide practical use. On the other hand, in optical communications, very few practical systems make use of the wave nature of light. Among the three elements of a wave—intensity, phase, and frequency (or wavelength)—most practical systems use a change in intensity for the transmission of information. In addition to a change in intensity, some cutting-edge research has incorporated the use of phase change, with the aim of improving system performance in long-haul high-capacity communications. However, a change in frequency (i.e., a change in wavelength) is only rarely used, as conventional devices have been unable to handle optical frequency control at high speeds. In March 2004, NICT successfully developed an optical FSK modulator that functions as an ultra-high-speed frequency control device. NICT has already completed transfer of this technology to a manufacturer, and the device is now commercially available as a modulation device. To date we have performed a variety of experiments using this device. One such experiment involved high-speed optical frequency shift keying (FSK) transmission, while another examined simultaneous transmission of a light intensity modulation (IM) signal and an optical FSK signal, intended for use in optical packet systems. The development of this optical FSK modulator has enabled control of the intensity, phase, and frequency of a light wave at high speed and with high precision. As a result we may expect implementation of a range of complicated functions comparable to the signal processing seen in wireless technologies. (See Fig. 1.)

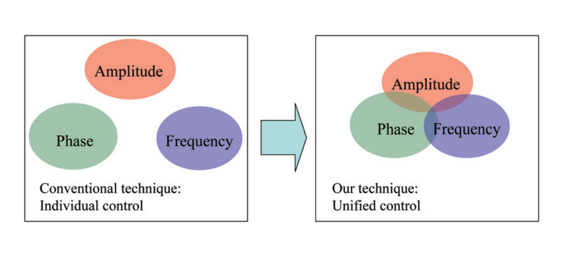

Fig. 1 *Integrated control of three elements of light wave (intensity, phase, and frequency)*

3 Optical FSK modulation technology

The optical FSK modulator integrates four optical phase modulators, as shown in Fig. 2. The device has three electrodes. When high-frequency electric signals are sent to two of the electrodes (RFa and RFb) with the phase of one signal shifted 90 degrees from that of the other, the frequency of the output light is shifted to the same extent as the shift in the signal frequency (this shift is referred to as the "modulation frequency"). The direction of the shift (designated as USB for the component with higher frequency, or designated as LSB for the component with lower frequency) can be controlled by the voltage applied to the remaining electrode (RFc). To switch the direction of the shift in light frequency at high speed, we have adopted a traveling-wave structure for the electrode[1]. (This structure enables high-speed operation by propagating

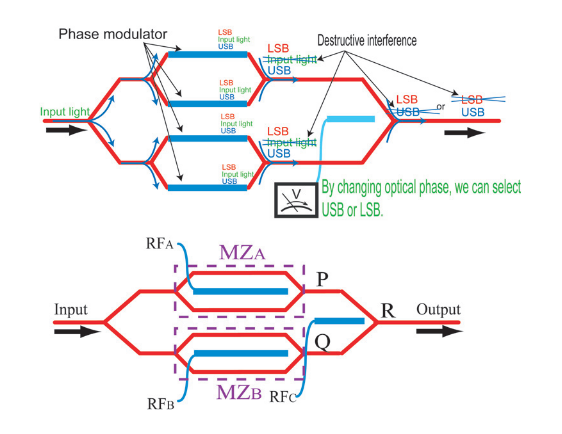

Fig.2 *Optical FSK modulator. Upper figure: schematic diagram. Lower figure: device structure*

the light and electric signals in the same direction at the same rate.)

Figure 3 shows the operating principle. The horizontal axis is the frequency, the direction of the arrow indicates the phase, and the dotted line indicates the frequency of the input light. At Points P and Q, both the USB and LSB components are generated. For the output light (Point R), the LSB components from Points P and Q have a phase difference of 180 degrees (i.e., of opposite signs) and cancel each other out. Consequently, only the USB components are output. The relationship between the phases of the LSB and USB components can be controlled by the voltage applied to the electrode RFc. Figure 4 shows a case in which the USB components cancelled out and the LSB components are output. The speed of this switching depends on the response speed of the electrode RFc. The upper limit of the frequency change depends on the operable frequency of the electrodes RFa and RFb. All three electrodes (RFa, RFb, and RFc) of the optical FSK modulator developed and evaluated by NICT feature the following characteristics: operable frequency (3-dB band) of approximately 18 GHz and switching speed of approximately 55 picoseconds.

The output light includes a slight amount of unnecessary components due to the generation of harmonics from the phase modulation. Nevertheless, these effects may be further suppressed by simultaneously supplying the third harmonics. In this manner, we achieved a conversion efficiency of −12.9 dB and a suppression ratio of 33.7 dB for unnecessary components with a frequency change of 7.5 GHz[2]. Figure 5 shows the configuration of the optical FSK transmission experimental system. With this system, we were able to achieve error-free transmission of 10-Gbps FSK signals over 95 km of a single mode fiber (SMF) without dispersion compensation. The frequency change in this case was 12.5 GHz[3]. With balanced reception using both the USB and LSB signals, we were able to improve the receiver sensitivity even further, succeeding in transmission over 130 km[4].

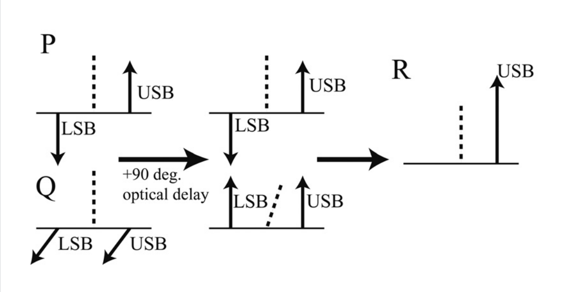

Fig.3 Operating principle of optical FSK modulator (USB: generation of components with upward frequency shift)

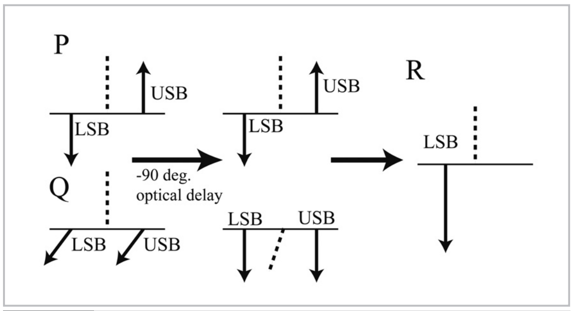

Fig.4 Operating principle of optical FSK modulator (LSB: generation of components with downward frequency shift)

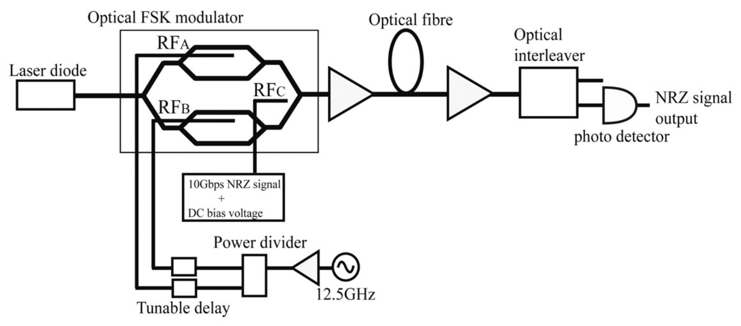

Fig.5 10-Gbps FSK transmission experiment

4 Optical label processing based on optical FSK modulation technology

The FSK/IM signal (an IM signal for the payload and an FSK signal for the label signal) can be generated by an optical FSK modulator and an optical intensity modulator connected in series. Figure 6 shows the experimental system and the results of measurement (the waveforms of the demodulated IM and FSK signals and the signal waveform after removing the label). The IM signal is transmitted at 10 Gbps and the FSK signal is transmitted at 1 Gbps. We can demodulate the IM signal by directly inputting the FSK/IM signal into the optical detector. On the other hand, we can demodulate the FSK signal with the optical detector by passing the FSK signal through an optical filter that can separate the USB and LSB signals and processing this signal by FM-IM conversion. We have confirmed error-free demodulation of both FSK and IM signals[5].

When we treat the FSK/IM signal with carrier-suppressed double-sideband modulation (amplitude modulation with the input components suppressed by interference) and use an optical filter to extract the same frequency component as that comprising the input light, we can obtain a signal equivalent to a pure IM signal, independent of the state of the FSK signal. As shown in Fig. 6, we obtained a good waveform for the demodulated IM signal without the FSK signal component and confirmed error-free demodulation. We can superpose a new FSK signal onto the demodulated IM signal when we input the latter into another FSK modulator. This method can change the label information (FSK signal) without converting the optical signal into an electrical signal (referred to as a “label swap”)[5].

5 High-density transmission technology

When the frequency shift is larger than the bit rate of the FSK signal (i.e., with wideband FSK), the two components have little overlap on the frequency axis, their spectral forms are independent of the phase relationship between the components, and the effect of the phase change on the demodulation characteristics is assumed to be small. To improve the efficiency of frequency use, FSK with small frequency changes (i.e., narrowband FSK) is effective. However, as the USB and LSB components overlap in such a case, the spectral form and the demodulation characteristics significantly depend on the phase relationship between these components. An FSK signal with phase continuity secured during frequency switching (with CPFSK, or Continuous Phase FSK) has a compact spectral form and superior demodulation characteristics. The FSK modulator does not generally provide

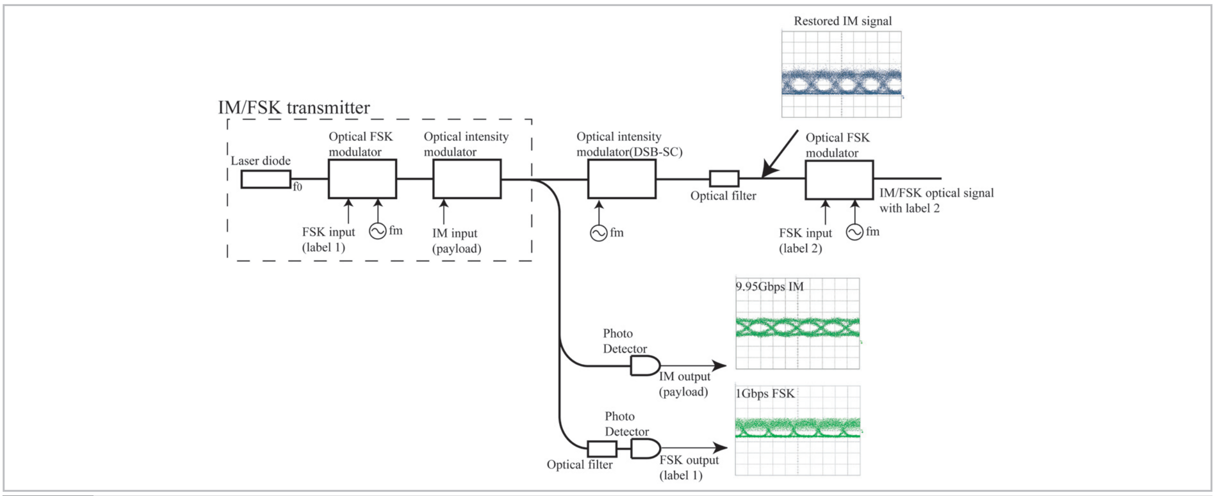

Fig.6 *Optical label transmission based on optical FSK modulation and label swapping*

optical phase continuity during frequency switching, and this switching is usually accompanied by rapid phase change. However, a CPFSK signal can be generated by synchronizing the signals used to generate the USB and LSB components (RFa and RFb) and the base band signal for frequency switching (RFc)[6]. The amount of the frequency shift is adjusted to half of the bit rate, B; in other words, the frequency interval between USB and LSB is adjusted to equal B, and switching is performed when the phases of the USB and LSB are in agreement. In CPFSK, the phase changes continuously by 180 degrees per bit. Figure 7 shows the results of the 10-Gbps CPFSK modulation experiment. We have confirmed that our method provides approximately the same sensitivity as a phase modulation method studied widely by other organizations (specifically, DPSK, or Differential Phase Shift Keying). CPFSK is also characterized by greater suppression of higher frequency components relative to DPSK, so that we can expect CPFSK to reduce interference between adjacent channels in high-density transmission. It is important to change phase continuously during frequency switching in CPFSK modulation. In contrast, it is possible to use a rapid phase change during switching to generate optical UWB (ultra-wideband) signals[7].

Setting as our goals a further increase in speed and more complicated functions, we have succeeded in developing a multi-functional modulator that supports high-speed signals—at 40 Gbps or higher—and have demonstrated 40-Gbps optical FSK modulation using this modulator[8]. This device can perform accurate frequency modulation, amplitude/intensity modulation, and multi-level phase modulation; moreover, the design incorporates 100-Gbps DQPSK (Differential Quadrature Phase Shift Keying) to ensure compliance with the 100 GbE next-generation Ethernet standard[9]. The modulator offers the highest transmission speed per channel available anywhere, and is also the fastest modulator using a signal format with highly efficient frequency use. As of March 2006, this multi-functional modulator is by far the world's fastest device capable of controlling optical phase and frequency. It also offers superb accuracy, with higher quality output light than that provided by the conventional combination of two or mode modulators, as demonstrated in the transmission experiment described below based on 80-Gbps DQPSK modulation (Fig. 8 (a)).

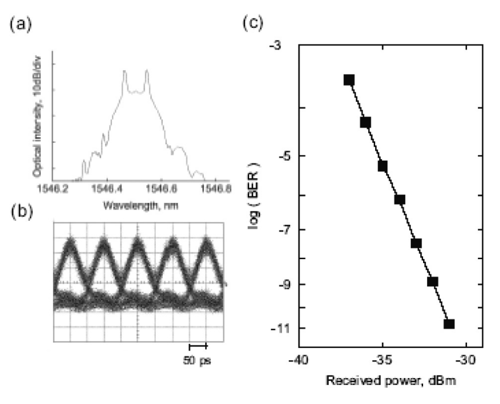

Fig.7 *High-density transmission using optical CPFSK modulation (a) optical spectrum, (b) demodulated signal waveform, and (c) bit error rate*

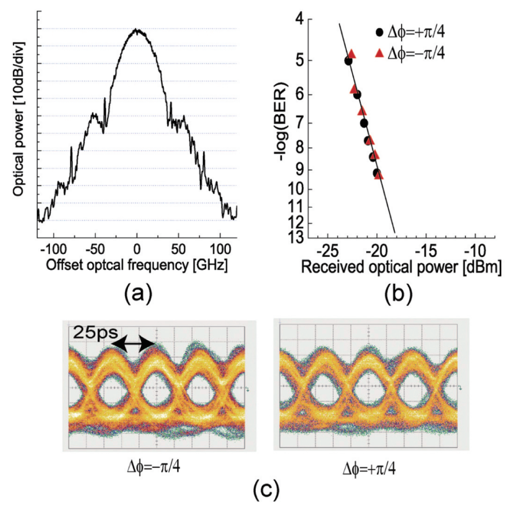

Fig.8 *High-density 80-Gbps transmission based on DQPSK modulation (a) optical spectrum, (b) bit error rate, and (c) demodulated signal waveform*

6 Variable delay technology

Next, we discuss variable optical delay based on optical frequency control using modulators[10]. To avoid collisions in optical packet exchange, variable optical delay technology is used to construct an optical packet buffer. A variety of methods have been proposed, including switching fibers and the use of many light sources. However, these methods have a range of problems, including generally complicated structures. On the other hand, we can implement variable delay with a simple structure using an optical SSB modulator (optical frequency shifter). The amount of this delay can be electrically controlled. As shown in Fig. 9, this structure involves an optical input/output unit consisting of an optical fiber loop equipped with an optical SSB modulator, and an FBG (Fiber Bragg Grating) sandwiched between two circulators. Light within the reflection band of the FBG circulates in the optical loop. When this light is input from the optical input port, it is reflected by the FBG and output without entering the loop. Light outside the reflection band propagates from the optical input port to the optical loop and from the optical loop to the optical output port. Thus, while the light within the reflection band is output without entering the optical loop, the light outside the reflection band is output through the optical loop with a time delay corresponding to a single lap of the loop. Operating the optical SSB modulator shifts the optical frequency in the loop, so that the input light outside the reflection band may be converted into light within the reflection band. Figure 10 shows the spectrum of light circulating in the optical loop. The input light, at a frequency slightly outside the reflection band, is processed with the SSB modulator to arrive at a frequency within the reflection band and circles round the loop. The frequency continues to change while the light is circling through the loop, so that the frequency exceeds the reflection band after a set number of laps; the light then exits the loop and is extracted from the output port. Denoting the reflection bandwidth as fr and the frequency shift by the optical SSB modulator as fm, the light circles around the loop n times when the relationship n fm > fr > (n−1) fm holds. Thus, the number of laps can be controlled by changing the value of fm. We processed the input light using pulse intensity modulation and measured the change in delay in the loop from the time waveform of the output light. Figure 11 confirms that the amount of delay can be controlled by the RF signal frequency fm.

7 Conclusions

Here we have discussed the details and applications of a high-speed optical modulation technology that can form an important component technology for next-generation photonic network. We can now apply

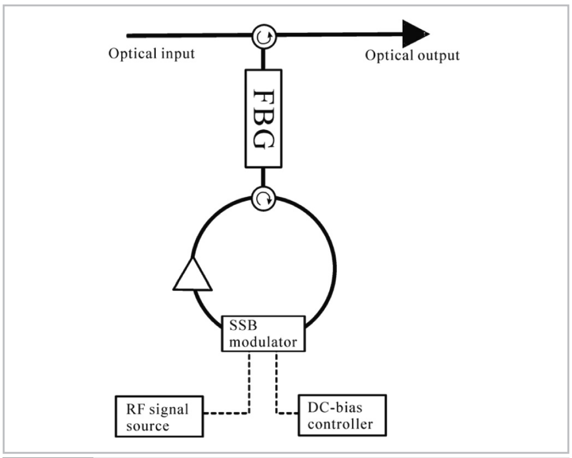

Fig.9 Configuration of variable delay

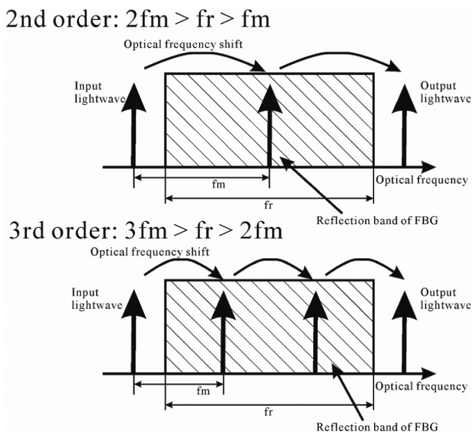

Fig.10 Principle of variable delay

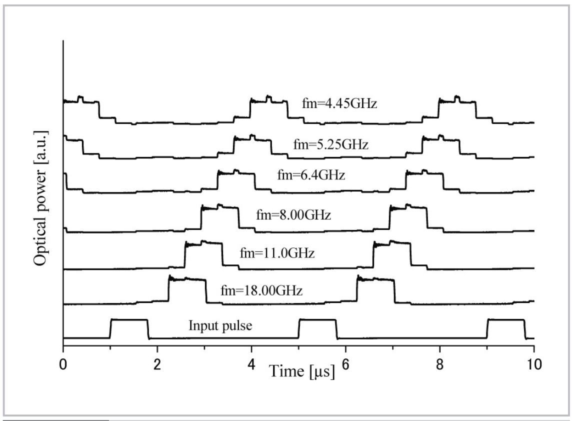

Fig.11 Delay controlled optical signal

advanced control over all elements of the wave/particle nature of light (amplitude, phase, and frequency). To date, the essential role of an optical modulator has been to convert the information expressed in electrical signals into light. In the future, optical modulators are expected to find use in diverse fields, from signal processing to control. In order to make these applications real, it will be important to promote research and development of modulators featuring new structures, optimized to suit the purposes of each application.

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High-speed Lightwave Modulation

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