3 Photonics Technologies

3-1 Optical Modulators for Photonic Sideband Management

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In this paper, we presented our recent works on development of optical modulators and subsystems. The modulators have new functions, such as optical frequency shift, modulation by radio-frequency-signal, etc, in addition to conventional ON/OFF keying. The target of our works is to provide particular functions for novel systems, such as radio-on-fiber system, optical packet switching, etc.

Keywords
Optical modulator, Resonance, Impedance, Optical fiber, Radio communication

1 Introduction

There are two types of optical modulation, which forms the key technology in optical communication systems: direct modulation, in which the light source (e.g., the laser beam) is directly controlled, and external modulation, in which an optical modulator is separate from the light source. Direct modulation is simpler in terms of system structure, but operating frequency in this case is limited to several GHz. External modulation systems, on the other hand, can operate within a wide range of frequencies—up to 30 or 40 GHz, including from direct-current to the millimeter wave band.

Optical modulators can in turn be categorized into two groups: those that make use of the electroabsorption (EA) effect of semiconductors or other devices, and those that use the electro-optic effect of lithium niobate (LN) or other materials. External modulation produced by modulators using the electro-optic effect results in only a small amount of phase-change components (chirp), and proves suitable for long-distance transmission applications (such as undersea cables) and in the optical transmission segments of large-capacity trunk lines. Although optical modulators using the electro-optic effect offer superb characteristics, they require long electrodes—up to several cm—to improve modulation efficiency, thus rendering integration difficult and adding to costs. Furthermore, in order to widen bandwidth it is imperative to move both the optical and electrical signals at the same speed and in the same direction—so-called “traveling-wave operation”[1]-[4].

On the other hand, EA modulators are characterized by small device size and low switching voltage, but these are inferior to LN modulators in terms of resistance to high power input, input wavelength characteristics, and chirp effects[5]-[8]. The advantages and disadvantages of these systems are to be taken into consideration when selecting a modulation method for a specific application.

Many research activities have been carried out to date with the aims of improving the operation speed of on/off intensity modulation and reducing power requirements. Our research group has been examining the basic function of optical modulators—that is, the transfer of digital signals over light waves—as well as new modulators and modulation systems that enable the processing of signals and information within the optical region. Concrete research themes include resonant-type modulators[9][10], which can be applied to radio-on-fiber communications, and optical SSB modulators[11], which can be used in optical frequency conversion applications. This paper introduces the present state of the semiconductor EA modulators and traveling-wave-type LN modulators widely used in digital modulation, and discusses the principles and features of resonant-type modulators and optical SSB modulators. We will also introduce a technology that enables advanced control of the optical sideband, resulting in millimeter wave generation[12][13] and tunable optical delay[14].

2 Conventional optical modulators and resonant-type optical modulators

Development of optical modulators for 40-Gbps optical communication systems is currently underway, and has in fact already yielded commercial results. The basic structure of a modulator calls for an optical waveguide and electrodes patterned on a material whose light transmissivity and refractive index vary according to the change in the externally applied electric field. EA modulators draw on the change in optical absorption of a semiconductor. On the other hand, LN modulators use the change in the refractive index caused by the electric field; therefore, they employ a Mach-Zehnder structure to produce a variation in intensity corresponding to the optical phase change. To enable on/off operations using only several volts, the interaction length between the light wave and the electricity—that is, the electrode length—must be approximately 100 μm in the case of the EA modulator, and several cm in the case of the LN modulator. When the electrode design does not incorporate a distributed constant circuit, and forms an optical waveguide with two sandwiching electrodes, the simplest equivalent circuit is achieved by a series connection of interelectrode capacitance and resistance induced by conductor loss. If the electrodes are shortened, capacitance is reduced, widening the operating bandwidth. However, this results in a problematic increase in the voltage required for switching. In the case of the LN modulator, the modulation efficiency per unit length of electrode is low; therefore, it is imperative to use long electrodes. Consequently, the design must incorporate the principle of a distributed constant circuit. To modulate electrical signals containing high-frequency components whose wavelengths are equal to or shorter than the device size, it is necessary to consider the effect of delay in light propagation.

When propagation velocity differs between the electric signal and the light wave, the phase of the electricity is reversed as viewed from the optical side, even if the electrodes are lengthened, and this does not lead to the improvement of modulation efficiency. To resolve this issue, the design must ensure that the propagation velocity is the same for the electricity and for the light wave (velocity matching). Generally, the LN dielectric constant (refractive index) for electricity is larger than that for light. The cross-sectional structure of the electrodes was therefore modified to reduce the effective refractive index for the electrical signals. Specifically, measures adopted included the use of ridge-structured or thick electrodes[15] and thinning of the LN section[16][17].

The design of the cross-sectional structure must not only ensure velocity matching but must also fulfill another requirement: to increase the overlap integration (overlapping of optical and electrical signal fields) to match impedance with that of a 50-ohm driver circuit. Currently, attempts are underway to increase modulation efficiency through the modification of materials. For example, stoichiometric LN with strictly controlled composition has a much larger non-linear effect than seen with conventional LN. These attempts are in addition to efforts in the development of optical modulators using organic materials[18][19]; however, these efforts have revealed a number of problems, such as a lack of stability under atmospheric conditions.

Since the electrodes are short in EA modulators using semiconductors, they are often designed as concentrated constant circuits; this approach notwithstanding, recent years has seen active research on traveling-wave-type EA modulators aimed at achieving wider bandwidths. Since the length of electrodes for EA modulators is less than 1/10 of those used in LN modulators, velocity matching is not very critical. Design based on the principle of the distributed constant circuit ensures a wider frequency bandwidth and maintains constant impedance, thus contributing to increased speed. In LN modulators, it is possible to reduce the effect of phase reversal induced by unmatched velocities through the use of electrodes with a periodic structure[20], or by reversing the orientation of crystal polarization[21]. Moreover, with a little ingenuity in the design of the polarization reversal cycle and pattern, modulators offering a variety of useful functions could be produced[22].

A resonant-type modulator uses the resonance phenomenon in the distributed constant line to generate a standing wave with high-amplitude voltage on the electrodes, resulting in improved modulation efficiency. While a conventional modulator featuring traveling-wave operation works within a wide frequency range, from direct-current signals to millimeter waves at several dozen GHz, a resonant-type modulator is designed to operate in a specific range centering around the resonance frequency; therefore, application of this type of modulator to radio-on-fiber systems and polarization scramblers appears highly promising.

Resonant-type modulators allow for high-efficiency modulation through the use of electrodes that are shorter than those required by traveling-wave-type modulators. Figure 1 shows an example of the structure of a resonant-type modulator with double-stub structure electrodes. The diagonal sections of the electrode permit adjustment of impedance. The resonant-type modulator shown in Fig.2 features electrodes of asymmetric resonant structure. The shorter electrode serves two functions: adjusting impedance and serving as a modulation electrode. Figure 3 shows an

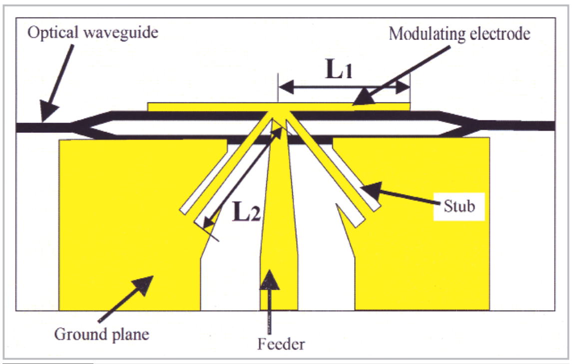

Fig.1 Structure of resonant-type optical modulator (double-stub structure electrodes)

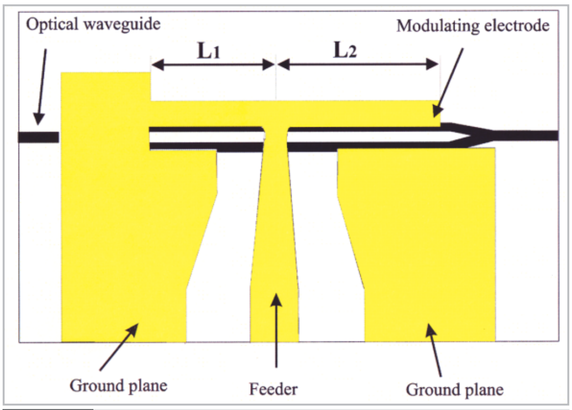

Fig.2 Structure of resonant-type optical modulator (asymmetric resonant structure electrodes)

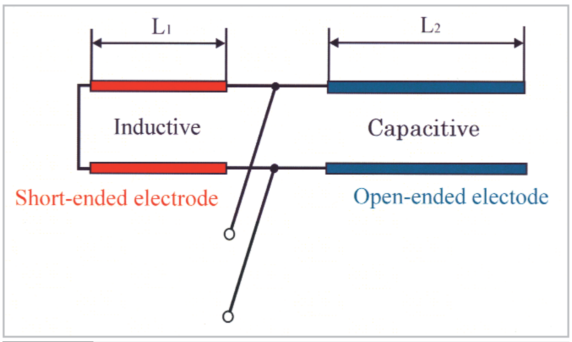

Fig.3 Equivalent circuit model of asymmetric resonant structure electrodes

equivalent circuit model with asymmetric resonant structure electrodes. These resonant electrodes produce increased voltage while preventing impedance dropping by combining the series resonance of the distributed constant line and the parallel resonance of the two-line circuit.

When a feeder is connected to a section near the node of the standing wave generated on the distributed parameters line, the line changes to a state of series resonance, producing a voltage on the electrodes that is greater than the feeding point voltage. However, since the impedance at the feeding point becomes extremely low during series resonance, the feeding point voltage itself drops, counteracting the increased voltage on the electrodes. If the electrode is shortened to just below the length corresponding to the resonance condition, a capacitive load results. With the connection of an inductive load to this in parallel, and adjustment of the size of the inductive load to match the capacitive load, the resulting parallel resonance significantly increases impedance. This results in both an increase in voltage (through the series resonance of the line) and an increase in impedance (through the resonance of the parallel circuit), enabling the generation of a large voltage on the electrodes and high-efficiency modulation. Impedance matching in this case is not necessary, but the feeding point impedance must be high. In antennas and other devices, resonance and impedance matching are simultaneously secured in order to maximize power efficiency.

In a modulator, however, improved power efficiency is not essential; the main purpose is to generate a high-amplitude voltage on the optical waveguide. Figure 4 shows an example of the modulation characteristics of asymmetric resonant structure electrodes. $V\pi L$ (an indicator expressing the modulation capacity per unit length of electrode; note that a smaller value indicates higher efficiency) was 3.15 Vcm at 6 GHz. Considering that a typical traveling-wave-type modulator exhibits a value between 20 and 50 Vcm, this result indicates that compact and high-efficiency modulators can be constructed using resonant electrodes.

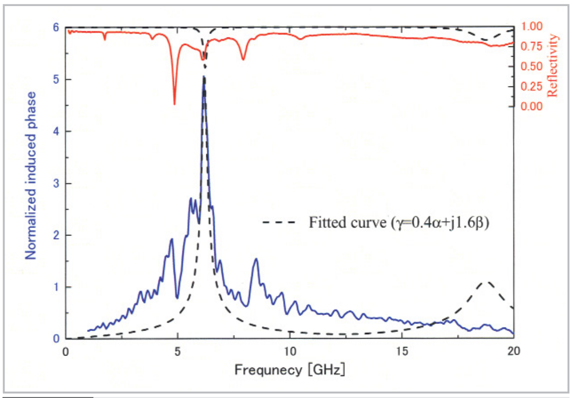

Fig.4 Optical response characteristics of resonant-type modulator (asymmetric resonant structure electrodes)

In a traveling-wave-type modulator, optical modulation works efficiently only for components for which the direction of optical propagation is the same as that of the electrical signals. In contrast, in a resonant-type modulator a standing wave is generated on the electrodes. Therefore, it can modulate the light wave components traveling in both directions. The reflection-type optical modulator (Fig.5) makes use of this phenomenon, and is capable of achieving twice the modulation efficiency of the resonant-type modulator. Figure 6 shows typical optical response characteristics. With an electrode length of 29.6 mm, $V\pi$ (voltage necessary for switching) of 2.9 V was achieved in the 7-GHz band. This performance ranks as the world's best for a modulator employing a commercial LN process.

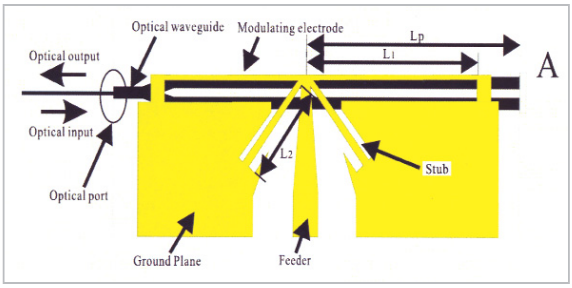

Fig.5 Reflection-type optical modulator with double-stub structure electrodes

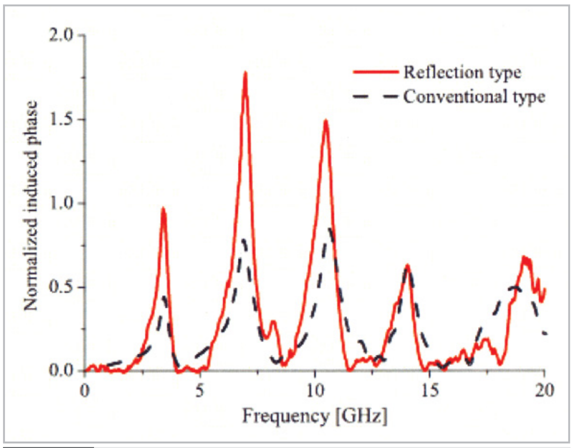

Fig.6 *Optical response of reflection-type optical modulator with double-stud structure electrodes*

3 Optical SSB modulators

Figure 7 shows the structure of an optical SSB modulator. Two sub-Mach-Zehnder waveguides (MZa, MZb) are arranged parallel to each arm of the main MZc[11]. The operating principle is as follows. A single-frequency RF electric signal ($\varphi\cos\Omega t$) is input to the RFa port, where incident light is described by ($\exp(j\omega t)$); at the same time the signal ($H[\varphi\cos\Omega t] = \varphi\sin\Omega t$) obtained by converting the single-frequency RF electric signal is input to the RFb port. Here, φ represents the modulation index, and ω and Ω are the angular frequencies of the light wave and the RF signal, respectively. Then, an appropriate bias is applied through the DCa port to create a phase difference ($\pi/2$) between the light waves passing through the two arms of MZc. When a phase difference (π) is created between the light waves passing through the two arms MZa and MZb, the optical spectrum at the final multiplexing point is expressed by the following formula (fourth-order and subsequent components are ignored):

$$e^{j\omega t}\left\{\left(e^{j\varphi\cos\Omega t}+e^{-j\varphi\cos\Omega t}e^{j\pi}\right)+\left(e^{j\varphi\sin\Omega t}+e^{-j\varphi\sin\Omega t}e^{j\pi}\right)e^{j\pi/2}\right\}$$
$$= e^{j\omega t}\left\{J_{-3}(\varphi)\,e^{-3j\Omega t}+J_{+1}(\varphi)\,e^{j\Omega t}\right\} \qquad (1)$$

Components of odd-number orders (including the zero-th order), as well as the negative first-order component, are suppressed, leaving only negative third-order and positive first-order spectral components. When the negative third-order component is sufficiently small, the output light wave contains a spectral component (upper sideband) resulting from the optical frequency shifting for an amount equaling the RF signal frequency. Changing the bias voltage setting outputs the lower sideband component. Figure 8 shows the spectrum of the output light wave after modulation using a 7.5-GHz sine wave, illustrating the optical frequency shift as a function of the RF frequency (J_0 corresponds to the input optical frequency).

SNR can be improved through simultaneous feeding of the third-order harmonics of the RF signal[23]. Using this method in our experiment resulted in an SNR of 35.4 dB. Conversion efficiency was 7.2 dB, and optical loss in the waveguide was 5.7 dB. By varying the RF frequency and DC bias, it is possible to secure high-speed and stable switching of the optical frequency, opening the door to applications in optical FSK systems and optical UWB signal generation[24].

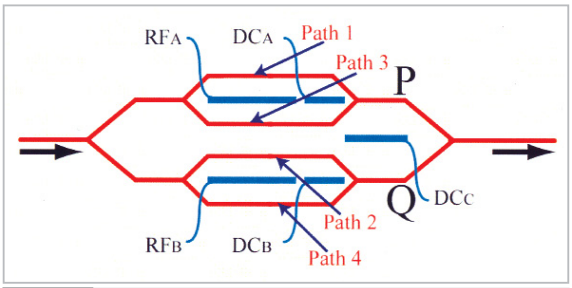

Fig.7 *Optical SSB modulator*

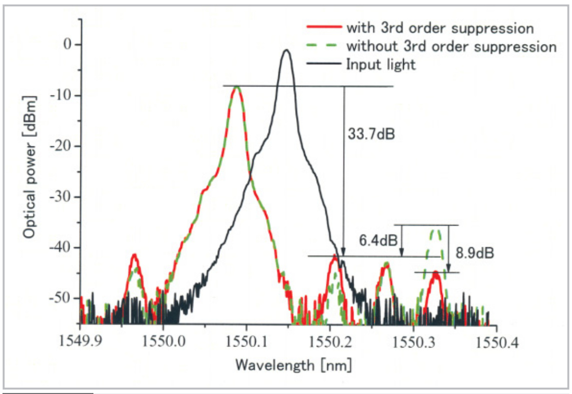

Fig.8 *Spectrum of output light wave shifted by optical SSB modulator*

4 Photonic sideband management technology

Conventionally, optical modulators were used primarily in applications involving the transmission of information via light waves. However, by controlling the sideband generated by the optical modulator, it is possible to create new functions that take advantage of the multiple useful characteristics of light waves. Below is an introduction of optical frequency conversion using reciprocating optical modulation, in addition to a discussion of tunable optical delay using millimeter wave generation and an optical SSB modulator.

To obtain an optical signal modulated at high frequency, the electrical signal applied to the modulator normally must be at a high frequency. However, an electrical circuit produces greater loss at higher frequencies, and further, it is difficult to generate and amplify this type of high-frequency electrical signal. As a result, the performance of an optical modulator is limited by the electrical circuit section. In contrast, reciprocating optical modulation, in which light is passed back and forth several times through the modulator, produces high-frequency modulated optical output at an integral multiple of the frequency of the electrical signal. This can allow for lower frequency within the electrical circuit section.

In a sample modulator structure (see Fig.8) in which the frequency is increased by a factor of ten, the narrow-band filter allows only optical input to pass through, and reflects components at other wavelengths. The input that passes through this filter enters the optical modulator, and the output is fed to the band-limiting filter. If the band-limiting filter is set to allow light waves to pass only at frequencies that differ from the input optical frequency by more than five times the frequency of the electrical signal supplied to the modulator, then the upper and lower sidebands generated by the optical modulator can be reflected, and the reflected components are input from the output port of the optical modulator into the narrow-band filter, and again fed into the optical modulator. This process is repeated to generate a light wave at a frequency that differs from the input optical frequency by more than five times the frequency of the electric signal supplied to the modulator. Passing the output light wave through the band-limiting filter results in a modulation frequency 10 times greater than the frequency of the electric signal supplied to the modulator.

We conducted an experiment in which we applied a 5-GHz electric signal to the modulator to generate a light wave modulated at a frequency 12 times greater than that of the electric signal[13]. The RF signal obtained from the output light wave detected by a photodetector is shown in Fig.9. This indicates an extremely low level of degradation in signal purity. Changing the filter structure permits high-speed optical frequency conversion with a waveform switching speed of several ns. Figure 11 shows an example of 180-GHz optical frequency conversion using a 30-GHz electric signal[12]. Reciprocating optical modulation resulted in the generation of positive sixth-order and seventh-order harmonic components.

With the aim of improving operational stability and reducing reciprocating operation time, we have been working to develop an integrated reciprocating optical modulator[25][26]. The device measures 86 mm in length, and it takes 454 ps for light to make the round trip between the filters (See Fig.12). The filters have a reflective bandwidth of 0.38 nm, and feature a reflective bandwidth transient range (change in wavelength required to change transmissivity from -0.5 dB to -3.0 dB at the end of the reflection bandwidth) of 0.02 nm. The modulation signal is at 4.4 GHz, and the reciprocating order is 14. In our experiment a 61.6-GHz millimeter-wave signal was generated. Figure 13 shows the phase noise characteristics of the millimeter wave (60-GHz band) generated by the integrated reciprocating optical modulator. The reference signal was generated using the Agilent 83650B and 83557A signal generators. The phase

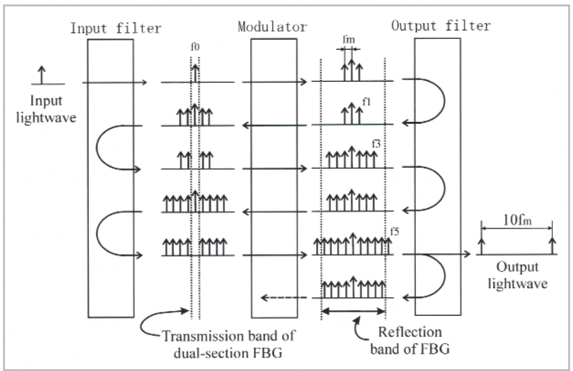

Fig.9 *Principle of reciprocating optical modulation*

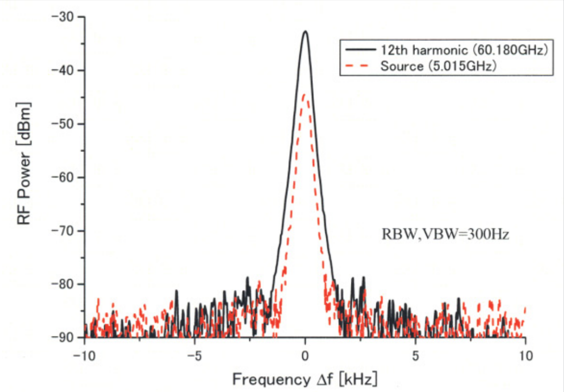

Fig.10 *Spectrum of millimeter wave (60 GHz) generated by reciprocating optical modulation*

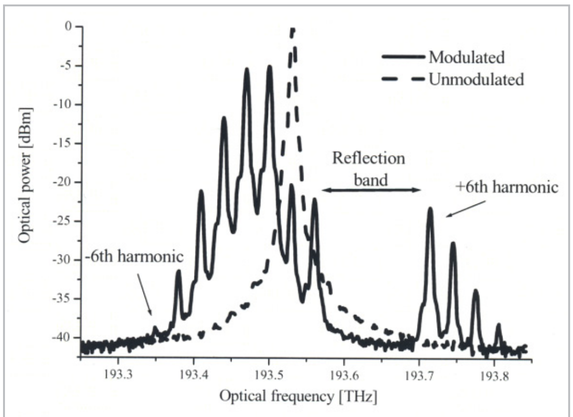

Fig.11 *Generation of higher-order harmonics (positive sixth-order and seventh-order) generated by reciprocating optical modulation*

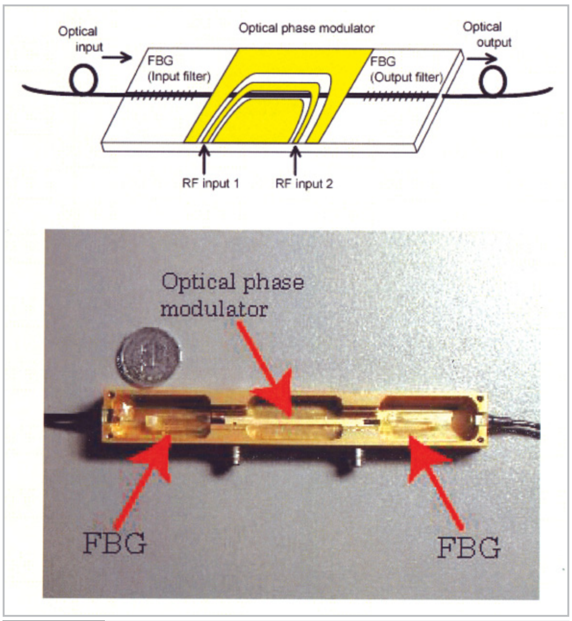

Fig.12 *Integrated reciprocating optical modulator*

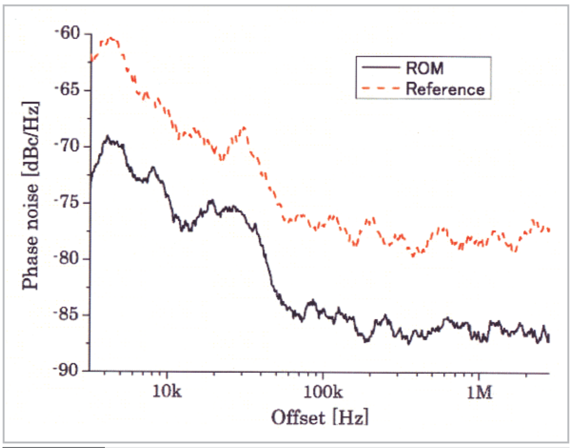

Fig.13 *Phase noise characteristics of millimeter-wave signal (ROM) generated by integrated reciprocating optical modulator and reference signal generator (Reference)*

noise in the millimeter-wave signal generated by the reciprocating optical modulation was lower than the noise level in the reference signal generator, attesting to the high purity of the generated signal. Furthermore, we observed virtually no fluctuation in intensity in operation without feedback stabilization control.

Next we will discuss the tunable optical delay obtained using an optical SSB modulator[14]. In an exchange of optical packets, tunable optical delay is used to configure an optical packet buffer to prevent packet collisions. Past technical proposals involved the multiple-fiber switching method or multiple light sources, but all of these proposals resulted in exceedingly complex structures. The use of an optical SSB modulator, on the other hand, allows for a simple tunable delay structure enabling electrical control of the amount of delay.

As shown in Fig.14, the optical input/output section is configured as a fiberoptic loop with an optical SSB modulator and two circulators, the latter separated by a Fiber Bragg Grating (FBG). Light waves of the FBG in the reflective bandwidth circulate within the optical loop. Input from the optical input port is reflected by the FBG and output from the optical output port without entering the loop. Light waves outside the reflective bandwidth proceed from the optical input port to the optical loop, then to the optical output port. While light waves in the reflective bandwidth are output without entering the optical loop, those outside the reflective bandwidth pass through the optical loop, thus producing a time delay corresponding to the time required for these waves to circuit the loop once.

When the optical SSB modulator is in operation, it shifts the optical frequency within the loop; therefore, optical input outside the reflective bandwidth can be converted to a signal within the reflective bandwidth. Figure 15 shows the spectrum of the light circulating within the loop. Optical input that deviates slightly from the reflective bandwidth undergoes a shift in optical frequency at the optical SSB modulator as it circuits the loop. Since the optical frequency continues to change as it circuits, the optical frequency again deviates from the reflective bandwidth after circling the loop a certain number of times; it then leaves the loop and is output from the output port.

If the reflective bandwidth is indicated by fr, and the amount of optical frequency shift caused by the optical SSB modulator is expressed by fm, the light wave circuits the loop *n* number of times when relationship, nfm > fr > (n - 1)fm, exits. Therefore, varying fm allows for control of the number of loop circuits. In our experiment we used pulse intensity modulation of the optical input and measured the change in the amount of loop-induced delay based on the envelope of optical output. As indicated in Fig.16, RF signal frequency, or fm, can be used to control the amount of delay.

5 Summary

In this paper we described high-speed optical modulation technology and its application to optical sideband control technology. Electrical circuit sections, including optical modulators and photodetectors, are becoming faster and adopting higher frequencies. Meanwhile, in the field of optical technology, devel-

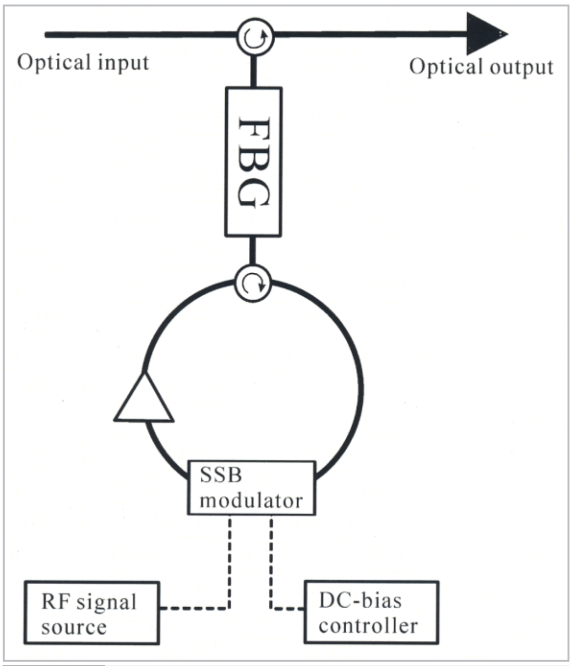

Fig.14 Tunable delay line using optical SSB modulator

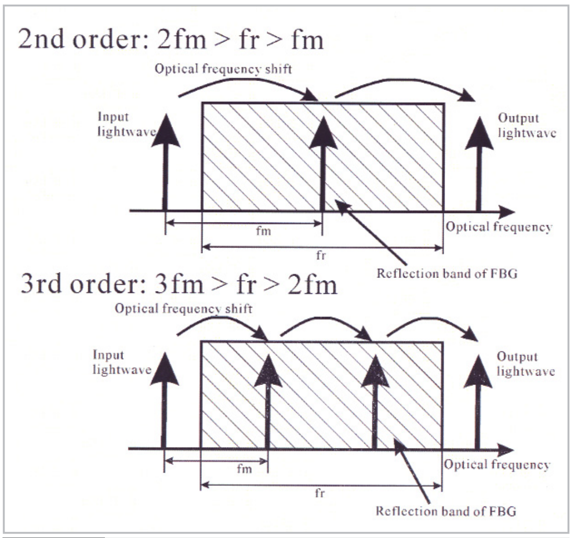

Fig.15 Operating principle of tunable delay line

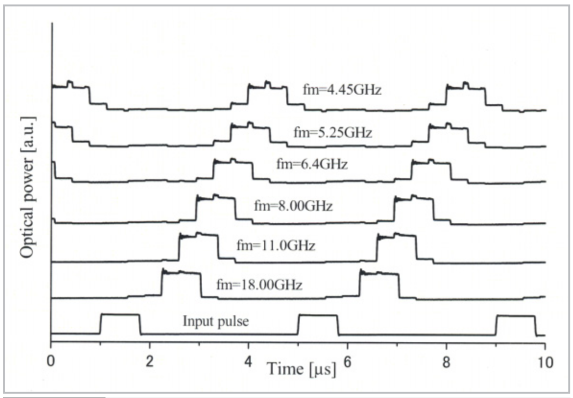

Fig.16 Envelope of light wave output from tunable delay line

opment of high-precision optical filters and AWGs continues to contribute to the realization of DWDM. Previously, signals up to a certain frequency band were processed electrically, and those above that frequency were processed optically. As such, the roles of optical processing and of electrical processing were clearly divided. However, the respective ranges handled electrically and optically have expanded, and in recent years have begun to overlap. For example, the wavelength resolution of many optical measuring instruments available today falls within a frequency bandwidth that can be easily handled by electrical instruments. The expanding and overlapping ranges of optical and electrical applications can lead to the emergence of new devices and systems that combine the advantages of these two methods. To date the key role of optical modulators has been to transfer electrically expressed information onto light waves, but it is our belief that optical modulators will find new applications in a variety of fields, including signal processing and control. Active research and development of modulators featuring new structures (such as the resonant-type structure) will be essential to such technological advancement.

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