2-3 Novel Photonic Devices Based on Electro-optic Modulation Technologies

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Recent progresses in optical modulation using electro-optic effects have renewed photonic signal processing technologies crucial in future advanced optical communication systems. NICT is now exploring novel functional photonic devices and subsystems based on electro-optic modulation technologies. In this paper, we review on recent research activities in NICT around these exotic technologies, picking up following three topics: (1) optical modulator array with patch antennas for weak radio-wave detection, (2) optical ring filter based on Ti-diffused $LiNbO_3$ waveguide loop for high efficient modulation, (3) photonic-electronic oscillator for self-oscillating optical comb generation.

Keywords
Electro-optic effect, Optical modulator, $LiNbO_3$ waveguide, Photonic device, Photonic subsystem

1 Introduction

There is a long history of optical modulators employing electro-optic effects[1]. Optical modulators were originally used to convert electric signals into optical signals. The waveguide optical modulator, which uses the electro-optical effect of lithium niobate crystals (referred to below as $LiNbO_3$ crystals, or simply as LN crystals), offers a means of high-speed, low-loss, and low-cost optical modulation, inspiring a number of ambitious studies[2]. Among today's advanced technologies, the $LiNbO_3$ waveguide optical modulator is crucial in the digital modulation of light by transmitters in backbone optical communication systems.

NICT is currently exploring novel functional photonic devices using optical modulation technology. These efforts are aimed at pioneering photonic devices with innovative functions, transcending the conventional concept that optical modulation may be used solely for electro-optic conversion in optical digital communications. To cope with complexity in future optical communication networks we are thus looking toward corresponding technological innovations in the signal processing crucial in network nodes. Due to improvements in the broadband characteristics of the optical modulator, it is now capable of serving as a basic technological element of a powerful optical processing system. Another notable trend in communication network technology relates to access methods, and so there is increasing demand for a hybrid optical/wireless system that will flexibly connect wireless and optical systems. From this viewpoint, the optical modulator device is also expected to serve as a powerful tool for seamless connection between such communication systems. These trends in technological demands are an inevitable outcome of recent developments in communication technologies, and so there is a pressing need for pioneering technologies that will offer functional connections between the worlds of optics and of electronics. One of our challenges is the production of a sophisticated device that can offer the full advantages of the optical modulator devices.

We have seen the development of a nano-scale fabrication technology for devices that has opened the door to the development of a device with complex electrode and waveguide structures. By applying the most advanced nano-scale fabrication techniques, it has become possible to create photonic devices with a range of novel functions. Additionally, the technology for optical modulators is also highly mature, and thus it is now possible to obtain highly precise, stable operation. The present state of technological maturity has allowed us to identify the required functions and also provides us with powerful tools for developing novel subsystems.

The present paper introduces the current progress in the following three technologies: (1) a $LiNbO_3$ waveguide optical modulator with patch antenna feed for optical-fiber-based wireless uplink, (2) an optical ring filter based on a Ti-diffused $LiNbO_3$ waveguide loop for high-efficiency optical modulation, and (3) a photonic-electronic oscillator for self-oscillating optical comb signal generation. In other words, these technologies are classified as devices that make effective use of microwave resonance in case (1), optical resonance in (2), and microwave-optical resonance in (3). In (1) and (2), the structures of optical modulator devices are improved, while in (3) the functionality of the optical modulator is extended.

2 $LiNbO_3$ optical modulator with patch antenna array

This section will present an overview of a wireless signal-detection device having a patch antenna feed as the modulator electrode of the $LiNbO_3$ optical modulator. This device has a function for detecting radio signals from remote places and may become an elementary technological component of optical-fiber-based wireless uplink systems. In order to detect weak radio signals propagating in free space, the detectors are cascaded in serial[3].

There is high demand for the realization of a hybrid fiber/wireless system that combines the advantages of the optical fiber network system, which permits low-loss long-distance transmission, and the advantages of a wireless network, which offers superior mobility and distribution[4]. In order to realize such a system we must pursue development of an interface that can mutually convert optical and millimeter-wave (microwave) signals. Past reports have discussed millimeter-wave generation technologies that use beat signals of laser lightwaves having different wavelengths[5] and reciprocating optical modulators[6], which may provide the downlink technologies required for converting optical signals into millimeter-wave signals. In contrast, there have been no such reports on effective uplink technologies, as these have been hindered by the difficulties presented by the weak received power and lack of an effective method for directly converting millimeter-wave signals into optical signals.

In this study, we propose an optical-millimeter-wave conversion interface having a modulator directly driven by the detected signal of an antenna equipped with a compact resonant-electrode-type modulator that displays high modulation efficiency per unit length[7]-[10]. By creating an array structure composed of these modulators, it may be possible to obtain high-efficiency modulation even if the detected signal is weak. Figure 1 shows an example of the structure of the proposed array of resonant-electrode-type modulators with antennas. In (a), a single patch antenna distributes the electric power to modulators and a phase modulation proportionally to the square root of the number of arrays N is obtained. In (b), each modulator has a separate antenna, and it is possible to obtain more effective phase modulation proportional to the number of arrays.

As shown in Fig. 2(a), the patch antennas were fabricated by etching of copper-foil-laminated double-sided printed substrates. On the front, the antenna has a square copper chip

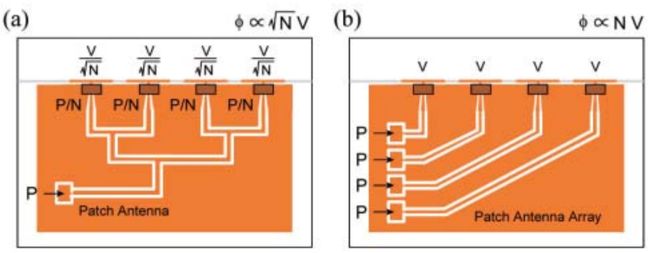

Fig.1 Resonant-electrode-type modulator array with patch antenna for millimeter-wave to optical-wave conversion

with a resonant frequency of 10 GHz, and its reverse side is grounded. Figure 2(b) presents the S_{11} (reflective) characteristics of the four antennas constructed. It can be seen that they have a bandwidth of approximately 1.0 GHz centered around 9.8 GHz, and so it may be concluded that the resonance of these antennas is matched to the modulation band of the resonant-electrode-type modulator. The modulator array and the patch antenna is hybrid connected.

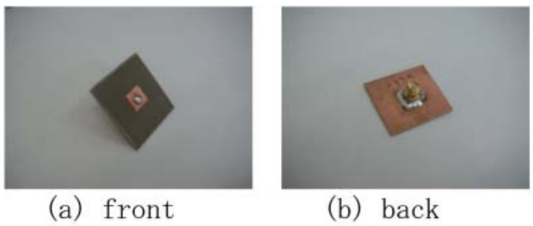

Fig.2 Constructed patch antenna

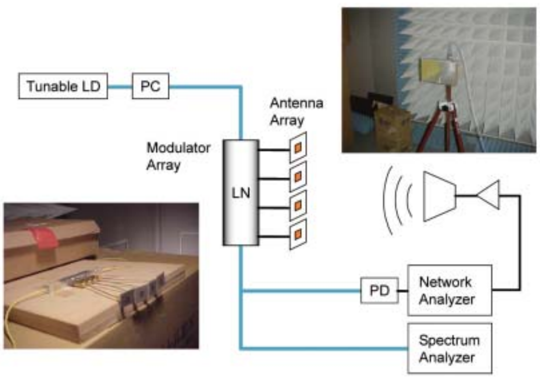

Fig.3 Experimental setup for the evaluation of signal reception for spatial transmission by the resonant-electrode-type modulator array with antenna

Using the modulator array, we carry out modulation experiments for free-space transmission. Figure 3 shows the systems for the spatial transmission experiment. The antennas were connected to each port of the modulator with feeder cables of the same length. RF signals generated by a network analyzer are amplified and emitted to free space via a horn antenna.

Figure 4 shows the spectrum of the received light. It can be seen that the spectrum is dependent on the number of modulators in operation that are connected to patch antennas. The distance between the antennas (horn-patched antenna distance) was set at 1 m. If an ideal situation in which the RF signal is input to each modulator in the same phase is assumed, then the amount of phase change per element is 0.01 rad. Based on the results shown in Fig. 4, the input power estimated from the half-wave voltage (15 V/π) is 0.048 V (−13.4 dBm) per modulator.

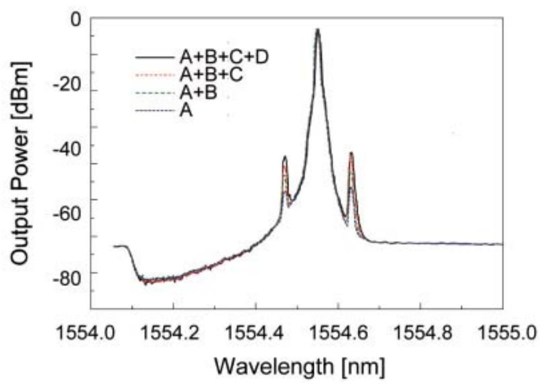

Fig.4 Optical spectrum (antenna distance: 1 m)

3 $LiNbO_3$ waveguide ring oscillator

This section introduces a waveguide optical ring resonator constructed on a $LiNbO_3$ substrate. Here, a high-Q (corresponding to high light confinement) resonator is created by making a ring circuit using the advantage in low-loss waveguide. Furthermore, since the waveguide is composed on a substrate made of an electro-optic crystal, the ring resonator can be applied for use as a high-efficiency optical modulator.

It is believed that this ring resonator, consisting of a ring circuit and a directional coupler, may be applied for use as an optical filter, and numerous past reports have discussed rings fabricated using semiconductor optical waveguides[12]. On the other hand, reports have also been issued on rings fabricated using $LiNbO_3$ (LN), aimed at improving the efficiency of optical modulation based on the electro-optic effect. The most significant feature of the LN ring as compared to semiconductor devices is that the former has larger ring structures, and so may be used for millimeter-wave and microwave filtering by light, which is an essential function of fiber/wireless systems[13]. However, the LN ring resonators previously reported all employed disk structures, which requires improving coupling efficiency with the fiber. In this study, we propose an optical ring filter based on a Ti-diffused $LiNbO_3$ waveguide loop and report on the basic characteristics of the fabricated device.

Figure 5 shows the structure of the ring filter based on the Ti-diffused $LiNbO_3$ waveguide loop. Due to the small difference in the refractive indexes of the core and the cladding of the Ti-diffused $LiNbO_3$ waveguide, the problem of large loss at the bend in the waveguide arose when creating a ring waveguide with a small radius. In the structure presented in Fig. 5, the ring resonator can be realized without a small-radius waveguide, where two reflectors and a directional coupler are effectively used. Thus, it is possible to obtain a low loss ring resonator. Since the reflector only reflects the light entering from one direction toward the opposite direction, it is possible to create a ring structure by positioning two reflectors so that they face each other and connecting them to the waveguide.

Figure 6 presents the measurement results for the optical transmission characteristics of the device constructed in this study. It also presents the theoretical values calculated by fitting using the resonance parameters (κ: coupling efficiency of the directional coupler; $\gamma 1$: loss of directional coupler; $\gamma 2$: loss within the ring structure; and $\gamma 3$: coupling efficiency between device and fiber)[14]. Z-cut substrate was used . The coupling efficiency was 92.5%, and the internal loss in the ring structure was 2.4 dB, and approximately 1 dB at the reflectors. The optical path length of the ring calculated from FSR is 61.74 mm. Additionally, it is possible to make the extinction ratio infinitely large with the ring resonator by adjusting the coupling efficiency, even when the ring has a loss[15]. Figure 7 presents the results of calculation assuming a κ value of 56.11%. The

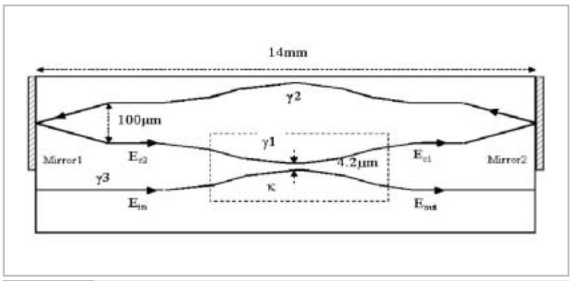

Fig.5 Architecture of waveguide ring oscillator

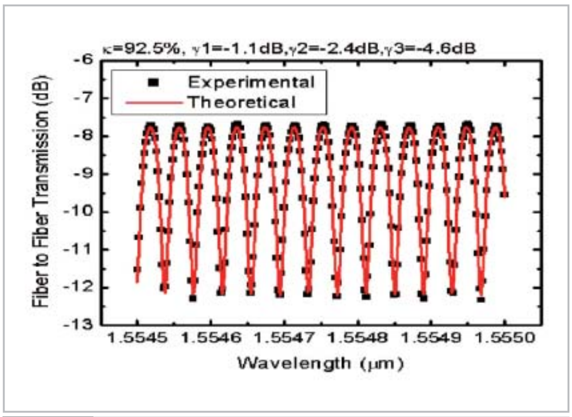

Fig.6 Optical transmission characteristics of a waveguide ring resonator

extinction ratio becomes larger than 30 dB, and it can be seen that it is possible to control the filter characteristics with high precision by adjusting the coupling efficiency using electro-optic effects. The Ti-diffused $LiNbO_3$ waveguide loop allows easy coupling between the ring and fiber, and it also offers electro-optic effects that are effective e even in the millimeter-wave band. Thus, we expect to see applications in high-speed controllable optical filters and high-sensitivity optical modulators. Furthermore, this configuration allows the characteristics of each element to be determined with high precision by parameter fitting.

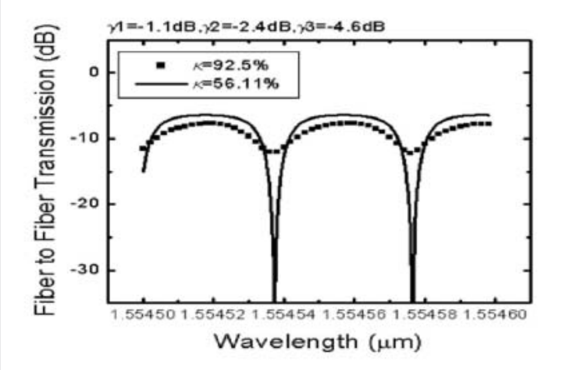

Fig.7 Controlling optical transmission characteristics by changing coupling efficiency

4 Self-oscillating optical comb generator

This section will introduce a self-oscillating optical comb generator using $LiNbO_3$ modulation technology. This device detects optically modulated signals from an optical modulator, and generates an optical comb by giving positive feedback to the modulator electrode. Inside the oscillator, oscillation is created by energy conversion between the microwave and optical signal, and the modulation signals are generated by self-oscillation. Harmonic signals are generated by the non-linear drive of the modulator and may be used for a multi-wavelength light source.

The technology for the generation of an optical frequency comb is expected to be widely applicable in various optical-control and signal-processing systems. The optical frequency comb generation shows promise for future application as an optical frequency standard for absolute frequency measurement, use in the remoting of local signals in the microwave and millimeter-wave bands[4], and use as a control signal for arrayed antennas used in radio telescopes for astronomical observations[4].

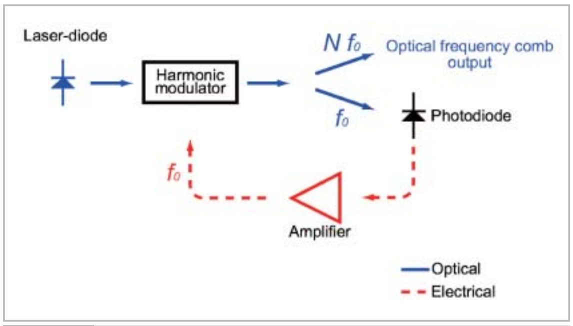

Fig.8 Concept of the self-oscillating optical comb generator

A more practical application of the comb generation is in a multi-wavelength light source for optical wavelength-division-multiplexed transmission systems. The most prominent feature of this optical frequency comb generation is that it can generate multiple frequency and wavelength components at equal frequency spacing. Presently, the most popularly used method for generating such signals requires multiple semiconductor laser sources, and studies have been applied toward the creation of semiconductor laser arrays. However, it is difficult to accurately control wavelength of each component of the comb signal . For example, a multi-wavelength light source in high-density WDM systems must have high precision in the generated wavelength for each component; however, wavelength control technologies ultimately lead to high system costs. Additionally, for optical measurements and remote millimeter-wave supply, it is necessary to perform optical-phase locking between multiple frequency components. However, phase locking between semiconductor lasers does not offer a practical solution to this problem.

To date, most studies have concentrated on mode-locked lasers using semiconductors and optical fibers[16] and on methods exploiting the optical modulation technology of $LiNbO_3$ modulators[17]. Studies have also been made on a super-continuum generation technology that uses the non-linear effects induced within optical fibers[18], effective in expanding the bandwidth of the optical frequency comb.

However, there are also problems with these optical frequency comb generation technology, such as the need for external oscillators and the inability to generate frequency combs by self-oscillation. In order to overcome these problems, our group has proposed an electro-optic oscillator featuring a built-in harmonic signal generator[19]-[21]. An electro-optic oscillator is a microwave generator that generates signals by detecting optically modulated components and performing positive feedback[22]. In the method proposed, an optical frequency comb is produced by self-oscillation while the optical modulator within the oscillator generates optically modulated harmonic components. In this system, the multi-mode optical frequency components do not contribute to the oscillation process, producing a state of single-mode oscillation. Thus, the system allows easy-to-achieve, highly stable system operation. Furthermore, since there is no instability, there is no need for complex control for the initiation and maintenance of oscillation.

Figure 9 shows the spectrum of the generated optical comb signal. One of the main features of this comb-generation method is its superior wavelength tunablity. Figure 9 (a) shows an example in which central wavelength control of the optical comb signal has been achieved by synchronous control of the optical filter of the feedback circuit[23]. The present system has been confirmed as capable of generating an optical frequency comb in the 100-GHz band having a wavelength tunable range of 10 nm or longer and at a frequency interval of 10 GHz. On the other hand, Fig. 9 (b) presents an example of a wavelength tuning function for a broader bandwidth, through replica generation[23]. The proposed system has been confirmed as capable of generating optical frequency combs in the 100-GHz band having a wavelength tunable range of 50 nm or longer and at a frequency interval of 10 GHz.

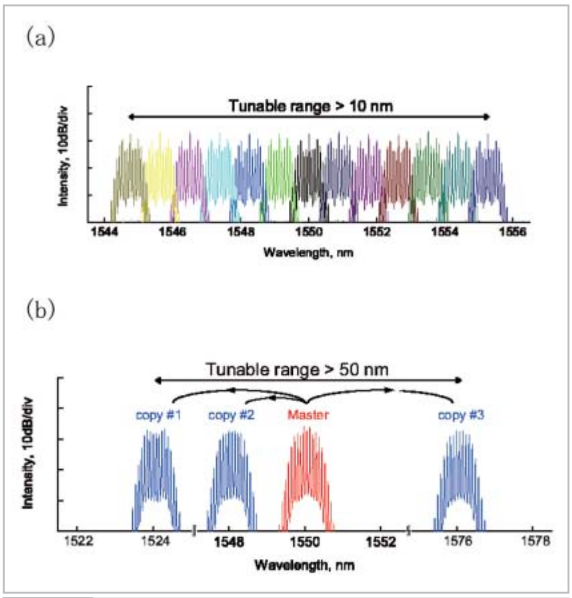

Fig.9 Optical spectrum of comb signal obtained by self-oscillation for (a) optical-filter synchronous control and (b) replica generation

5 Conclusions

This paper has introduced some topics related to optical modulator-type photonic devices developed at NICT in recent years. The relevant technologies are expected to serve as important elementary technologies for a next-generation photonic network.

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