Compact Low-power-consumption Optical Modulator

Eiichi Yamada†, Ken Tsuzuki, Nobuhiro Kikuchi, and Hiroshi Yasaka

Abstract

Optical modulators are indispensable devices for optical fiber communications. They turn light emitted from a laser diode on and off at ultrahigh speed and generate high-speed optical signals. By employing the “n-i-n structure” in the core layer, NTT Photonics Laboratories has developed an optical modulator that is less than one-tenth the size and consumes one-third the power of commercially available devices. This success is a major step toward broadband technologies that will reduce the load on the environment.

1. Introduction

With the progress of broadband technology, more and more network equipment is being installed. In addition, to handle the rapid increase in traffic, large-capacity large-scale networks are being constructed. All of that network equipment consumes a lot of power, which puts a heavy load on the environment. The best way to reduce the power consumption is to build individual components that consume as little power as possible. NTT Photonics Laboratories, which researches and develops various optical components for optical communications, has recently succeeded in developing a compact low-power-consumption semiconductor optical modulator by introducing a new structure [1].

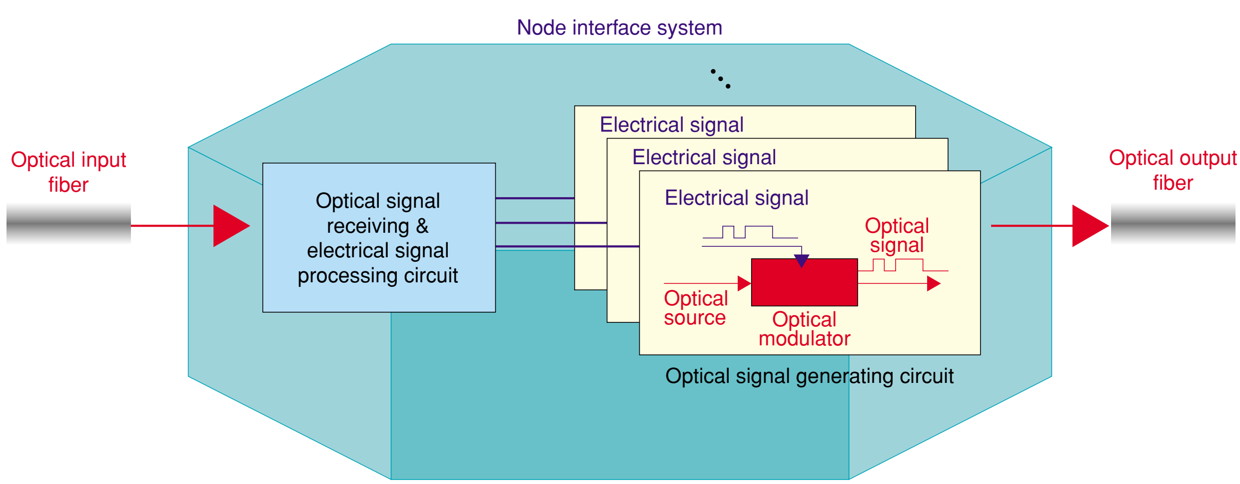

Fig. 1. Schematic view of a node interface system using an optical modulator.

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2. Conversion of electrical signals to optical signals

As shown in **Fig. 1**, in optical fiber communication networks, nodes installed in telecommunication buildings process optical signals received through optical fibers and send them out through other optical fibers. To enable them to be transmitted via optical fiber, the electrical signals must be converted into intensity-modulated optical signals. Since the modulation speed in access systems is relatively low, this conversion is performed by directly modulating the optical source, normally a laser diode (LD), with electrical signals. However, direct modulation of an LD causes a change in lasing wavelength, which is called chirping. Chirping poses a serious problem in optical fiber transmission in the backbone systems because it limits the modulation speed and the transmission distance. The solution is external modulation because it produces very little wavelength chirping. In external modulation, an optical modulator converts the fixed-intensity light emitted by the LD into an intensity-modulated optical signal.

3. Characteristics of various modulators

Most optical modulators use the electro-absorption (EA) effect in a semiconductor or the electrooptic (EO) effect in a dielectric material such as $LiNbO_3$. **Table 1** summarizes the characteristics of commercially available optical modulators and of those produced in this work. Various improvements, such as reduced power consumption, have currently been made in such modulators.

An EA modulator is compact and fast and can be driven at voltages below 2 V. An EA modulator monolithically integrated with an LD provides an optical source with a modulation speed of 10 Gbit/s. At present, EA modulator research is focused on improving performance and reducing cost, and EA modulators with a low driving voltage of 0.7 V [2] and 0.79 V [3] have been developed. On the other hand, optical modulators using the EO effect have been used in optical communication networks by NTT since the mid-1990s. The EO effect is a phenomenon where the refractive index changes when an electric field is applied to a solid or a liquid. The change in the refractive index is proportional to the applied electric field. This is called the Pockels effect, and it is commonly used for optical modulators.

The phase modulator and intensity modulator are optical modulators that use the EO effect. The phase modulator makes direct use of the phase change caused by the refractive index change. The intensity modulator is composed of a Mach Zehnder interferometer, in which the phase change is converted into an intensity change. Since there is very little wavelength chirping when a Mach-Zehnder modulator is used, it is the most popular optical modulator for long-distance backbone networks. Recently, there has been a trend for adopting a modulation format that includes phase modulation to improve spectral efficiency. Therefore, there is a growing need for optical modulators that use the EO effect, from which the phase modulation is derived.

A Mach-Zehnder modulator made of $LiNbO_3$ offers a large EO effect, small optical propagation loss, and good coupling efficiency to fibers. However, the driving voltage of commercially available $LiNbO_3$ Mach-Zehnder modulators is as high as 3 – 5 V, and the modules are as large as about 15 × 120 mm^2. In addition, a complex control circuit is needed because a driving condition change called “DC drift” occurs when DC voltage is applied. Attempts have been made to reduce the driving voltage of $LiNbO_3$ Mach-Zehnder modulators, and 40-Gbit/s modulation with driving voltages of 0.9 V has been demonstrated in a dual-drive operation [4]. Research on Mach-Zehnder modulators made of semiconductors such as GaAs and InP is proceeding. However, excess optical propagation loss and the difficulty of achieving high-speed driving have prevented these modulators from being used in practice.

We have solved these problems by introducing the “n-i-n structure” in the semiconductor layers. This novel structure allowed us to build a compact high-speed optical modulator with a low driving voltage.

Table 1. Characteristics of commercially available optical modulators and of those produced in this work.

	Driving voltage	Modulation speed	Chip size
EA modulator	2 V	10 Gbit/s	< 1 mm
$LiNbO_3$ modulator	3–5V	10–40 Gbit/s	~ 60 mm
This work	1V	10–40 Gbit/s	~ 5 mm

4. Structure of the semiconductor Mach-Zehnder modulator

A Mach-Zehnder modulator consists of optical waveguides. The cross-sectional geometry of a wave-

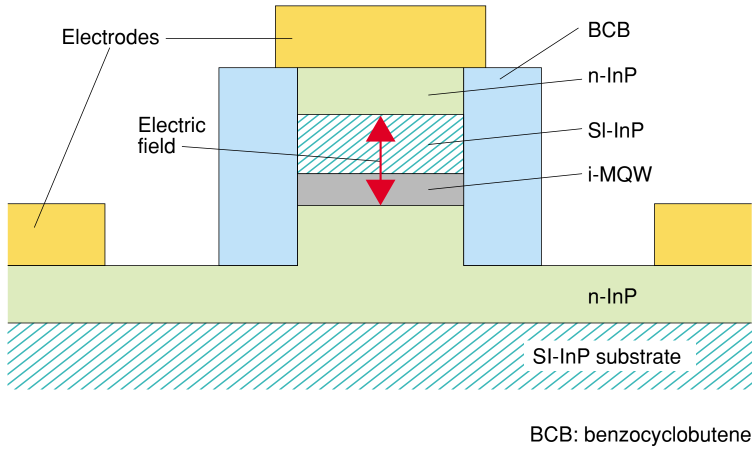

Fig. 2. Cross-sectional geometry of the n-i-n structure optical waveguide.

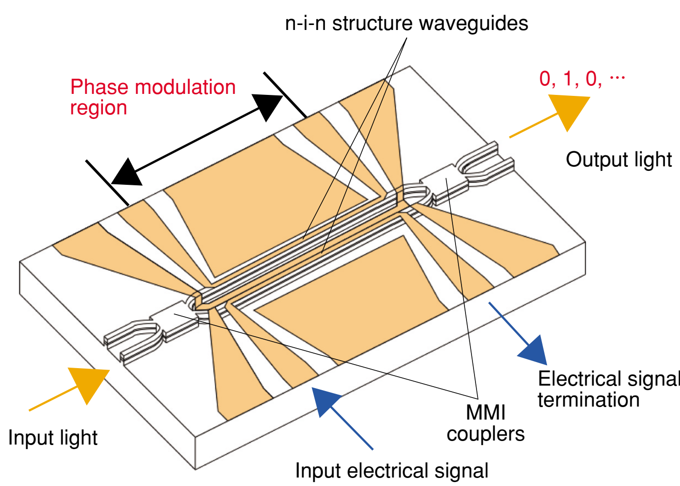

Fig. 3. Schematic structure of the n-i-n Mach-Zehnder modulator.

guide with the n-i-n structure is shown in **Fig. 2**. An n-InP cladding layer, undoped InGaAlAs/InAlAs intrinsic multi-quantum well (i-MQW), Fe-doped semi-insulating (SI) InP layer, and n-InP upper cladding layer were grown on the SI-InP substrate.

The electrical and optical signal losses of the n-type cladding layer, which is formed on both the signal and ground electrode sides, are less than 1/20th those of the p-type cladding layer normally used in semiconductor optical modulators. The Fe-doped SI-InP layer between the n-InP upper cladding and undoped waveguide core provides efficient current blocking. The SI-InP layer and undoped waveguide core layer are 1.0 and 0.3 µm thick, respectively. When voltage is applied to these layers, the intensity of the electric field increases greatly. Therefore, we can obtain an efficient index change as a result of the EO effect.

Since the refractive index change of InP semiconductor material is 1/7th that of $LiNbO_3$, the key to making an optical modulator using the EO effect practicable is to be able to efficiently apply a high electric field to the waveguide core layer. The width of the n-i-n waveguide is 1/4th that of the waveguide in a $LiNbO_3$ modulator, and the gap between electrodes is 1/30th to 1/50th. This makes it possible to apply 100 times the electric field and thereby perform optical modulation with a low driving voltage. The width of the waveguide and the gap between electrodes are very small in a semiconductor optical modulator. The excellent semiconductor micro-fabrication technologies developed by NTT Photonics Laboratories are what made the n-i-n structure possible.

The structure of an n-i-n Mach-Zehnder modulator is schematically illustrated in **Fig. 3**. The modulator

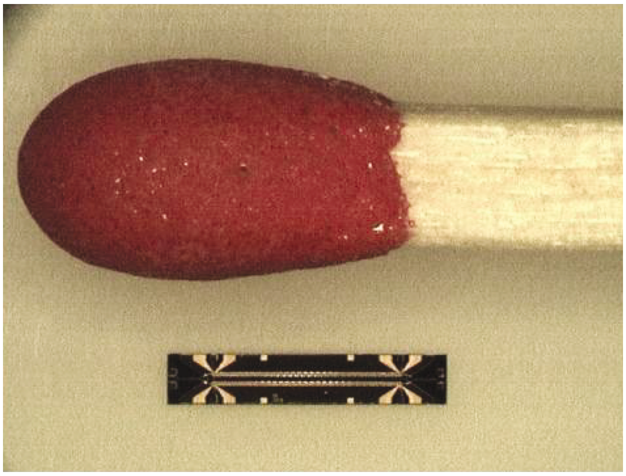

Fig. 4. Photograph of the Mach-Zehnder modulator chip.The chip size is 0.8×4.5 mm^2.

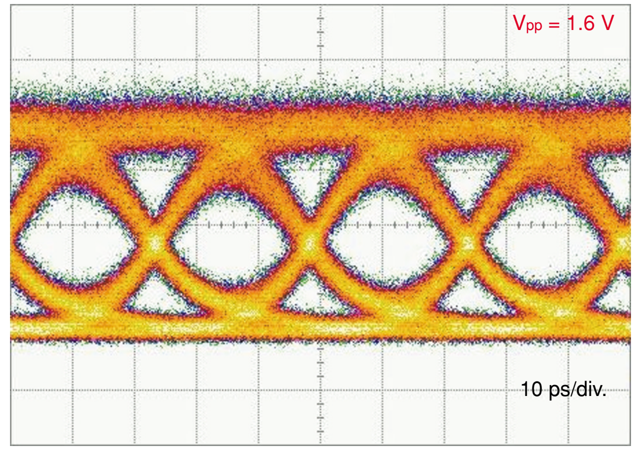

Fig. 5. Eye diagram at 40 Gbit/s. Driving voltage was 1.6 V.

consists of two 2×2 multimode interference (MMI) couplers and two parallel phase-shift n-i-n structure waveguides. First, input light is divided into two and sent into the two optical waveguides by one of the couplers. Then, when the electric field is applied to the n-i-n waveguide, the refractive index changes and the phase of the light transmitted in the waveguide also changes. The other MMI coupler couples the two optical waveguides, and the coupled light is introduced to the output port after the two coupled lights have interfered at the coupler. If the phases of the two lights coincide, the lights are summed and light appears at the output port. If they are opposite, the lights cancel each other and there is no output light.

The traveling-wave electrodes on the optical waveguides are important. The modulation speed greatly depends on the high-frequency characteristics of the traveling-wave electrode. The n-i-n structure waveguide makes it easy to design the traveling-wave electrodes, and the electrodes are much shorter than those in a $LiNbO_3$ modulator. It is therefore easy to match the velocities of the electrical and optical waves, and an operation bandwidth of more than 40 GHz can be obtained. In the n-i-n structure waveguide, although the optical confinement factor is large and refractive index modulation is efficient, electrode resistance affects the performance because the electrode cross section is very small. We have decreased the electrode resistance by introducing a 3-μm-thick Au electrode while maintaining the velocity and impedance matching.

A photograph of the Mach-Zehnder modulator is shown in **Fig. 4** in comparison with a matchstick. The chip size is 0.8×4.5 mm^2. The device length is less than 1/10th that of a conventional $LiNbO_3$ modulator. These modulators can be packaged in a very small module.

5. 40-Gbit/s modulation with low driving voltage

There is strong demand for optical transmission at 40 Gbit/s because of the recent increase in transmission capacity. **Figure 5** shows an eye diagram obtained for a 2^{31}–1 pseudorandom bit stream (PRBS) at 40 Gbit/s using a device with 4-mm-long electrodes. The driving voltage was supplied to one arm of the modulator. We obtained clear eye opening at a driving voltage of 1.6 V [5], which is about 1/3rd that of a $LiNbO_3$ modulator.

The Mach-Zehnder modulator has two traveling-wave electrodes, and supplying them with differential signals allows us to halve the driving voltage [6]. The n-i-n modulator can be driven at 1 V at 40 Gbit/s by employing a push-pull drive configuration.

6. Conclusion

The n-i-n Mach-Zehnder modulator is very attractive as a high-speed modulator because of its low driving voltage, small size, and simple operation. After we confirm its long-term stability and reliability, we will use it in optical network systems for the next generation.

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