Successful Preparation of KTN Crystals with the Highest Reported Electro-optic Effect and the Potential for Providing a Great Improvement in Optical Device Performance

NTT has successfully prepared KTN crystals ($KTa_{1-x}Nb_xO_3$) with the highest electro-optic effect*1 ever reported. In addition, NTT has developed film growth and lithographic techniques for KTN crystals that can be used to fabricate an optical waveguide with excellent optical transmission performance. An optical switch using these KTN waveguides exhibited a low driving voltage less than 1/10 that of conventional optical switches. This result clearly shows the excellent potential of KTN crystal in terms of optical device performance.

By using these KTN crystals, it should be possible to fabricate optical modulators and optical switches with a driving voltage one order of magnitude lower than that of conventional optical devices. This will provide a way to develop the next generation of highly functional devices.

KTN is a transparent optical crystal composed of potassium, tantalum, niobium, and oxygen. The first KTN crystal was synthesized in the 1950s and it is well known as a crystal with a very large quadratic electro-optic effect (Kerr effect), which determines device performance. However, KTN crystal has been considered an impractical material because it was difficult to grow.

NTT Photonics Laboratories found that precise temperature control is essential to grow a large crystal, and they successfully prepared 40-mm-square KTN crystals, which is a practical size. The electro-optic coefficient of these KTN crystals is about 600 pm/V, or 20 times larger than that of conventional $LiNbO_3$*2. This coefficient means that an improvement in device performance of at least one order can be expected.

Background

In recent years, the explosive growth in trunk line capacity has largely ended and the goal is now large-capacity and highly functional metropolitan or access networks. In order to achieve this goal, the size and power consumption of optical devices must be reduced and their functionality increased. Of these devices, optical modulators and optical switches made of conventional $LiNbO_3$ materials are especially important for the networks. However, these devices are large and have relatively high driving voltages as a result of the small electro-optic effect of $LiNbO_3$. Therefore, attention has been drawn to the development of novel materials with a larger electro-optic effect with a view to overcoming these problems. In addition, in the near future, highly functional materials are expected to be used to make high-speed and highly integrated optical signal processing devices for network innovation.

Technological points

(1) Technology for growing large and high-quality KTN crystals

NTT successfully prepared the largest KTN crystals ever grown (40 mm square × 30 mm long) by optimizing the growth conditions and achieving precise temperature control (**Fig. 1**). This crystal is at least 20 times larger than a conventional $LiNbO_3$ crystal.

(2) Waveguide fabrication technology

NTT has established KTN crystal films on substrates prepared from bulk crystals by using liq-

*1 Electro-optic effect: A refractive index change is produced when an electrical field is applied to some materials. If the relationship between this refractive index change and the applied electrical field is linear, it is called the first-order electro-optic effect (Pockels effect). A quadratic effect is called the second-order electro-optic effect (Kerr effect).

*2 $LiNbO_3$ (Lithium niobate) has the highest electro-optic coefficient among practical materials and is widely used in optical modulators for telecom applications.

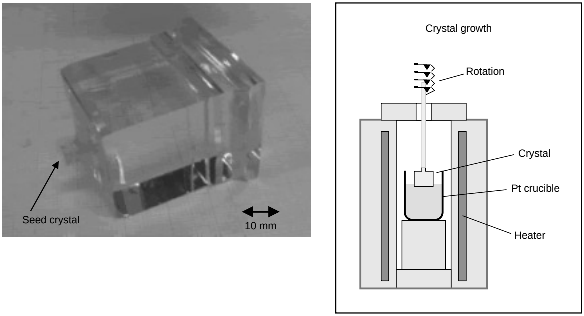

Fig. 1. Synthesized KTN crystal.

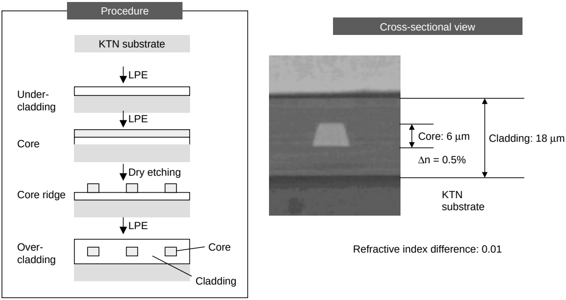

Fig. 2. Waveguide fabrication.

uid phase epitaxy (LPE)[*3]. High-quality KTN films with a controlled thickness of 5–10 µm for waveguide fabrication can be prepared by controlling the growth rate and suppressing any temperature fluctuation on the growth surface. This makes it possible to fabricate low-loss waveguides with a loss of 0.5 dB/cm[*4] by dry etching[*5]. Complex optical circuits can be fabricated with these technologies (**Fig. 2**).

*3 Liquid phase epitaxy is a crystal film growth technology where substrates are soaked in a solution to prepare specific crystal films on the substrate surface. LPE can grow high-quality crystal film with a high growth rate. .

*4 dB/cm is a unit that indicates the transmission loss of an optical waveguide. 0.5 dB/cm indicates about a 10% loss of transparency per centimeter.

*5 Dry etching is a lithographic technique using highly reactive species such as ions and radicals formed in a plasma (discharge). This technique is widely used for the lithography of crystals and glasses.

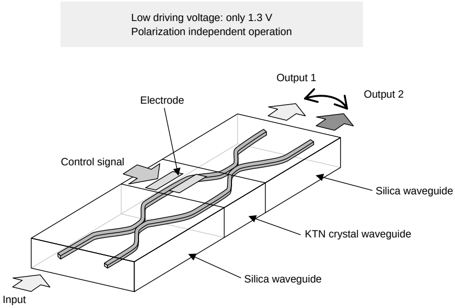

Fig. 3. KTN optical switch.

(3) Demonstration of optical switching

A Mach-Zehnder interferometer*6 was constructed using KTN crystal waveguides and a silica glass waveguide. An optical switch is operated by applying a voltage to electrodes prepared on the KTN waveguide surface. Optical switching at a very low voltage of 1.3 V was observed. Polarization-independent operation was also confirmed*7 and this is indispensable for optical switches. NTT has therefore made an optical switch with the lowest driving voltage yet reported and polarization-independent operation (**Fig. 3**).

*6 Mach-Zehnder interferometer: Interference is a phenomenon whereby two optical waves overlap thus intensifying or diminishing their amplitudes. A Mach-Zehnder interferometer is a device in which one optical wave is first split into two waves and then recombined into one wave to induce optical interference. Mach-Zehnder interferometers are widely used for telecom applications such as optical switches and optical modulators.

*7 Polarization-independent operation: Light is composed of two orthogonal vibrations that are perpendicular to the propagation direction. In general, the optical properties parallel and perpendicular to a waveguide substrate are slightly different. The optical performance thus changes depending on the polarization. In particular, electro-optic crystals have a large optical birefringence that depends on the optical axis. Therefore, these polarization-dependent properties are serious problems that must be overcome.

Future plans

In order to develop highly functional optical signal processing devices, NTT plans to proceed with large crystal growth and large-scale optical circuit fabrication with a view to demonstrating the very high potential of KTN crystals.

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