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KTN-crystal-waveguide-based electro-optic phase modulator with high performance index

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An electro-optic (EO) phase modulator with a low driving voltage that uses newly developed $KTa_{1-x}Nb_xO_3$ buried waveguides is described. The waveguide layers for the core and cladding were formed using liquid phase epitaxy techniques. The propagation loss was less than 0.5 dB/cm and the polarisation-dependent loss was less than 0.1 dB/cm. The EO phase modulator had a low $V_\pi \times L$ value of <1.5 cm V (4.0 V biased potential) and a fast response of 3 GHz.

Introduction: High-speed optical modulators with nanosecond operation are important components in systems designed to send/receive large amounts of information such as screen and/or moving image data. They are useful as transponders in metropolitan networks, which can send/receive modulated signals. Many kinds of modulator have already been reported that employ materials with electro-optic (EO) effects [1–3]. EO modulators that use $LiNbO_3$ (LN) are the most widely investigated. The electrode length for modulation is 5 cm although the driving voltage is less than 1 V [1]. There is a trade-off between driving voltage and modulation length and materials with high EO coefficients are needed to improve these two aspects of performance simultaneously. Thus, certain problems remain as regards the modulator due to the intrinsic properties of their materials. $KTa_{1-x}Nb_xO_3$ (KTN) crystals exhibit large quadratic EO effects [4]. However, it was difficult to fabricate EO waveguide devices using KTN crystals because of the difficulty in growing high-quality crystals and films. This Letter describes an EO phase modulator with a low driving voltage that uses newly developed KTN buried waveguides.

Waveguide and modulator preparation: We have successfully fabricated a KTN buried waveguide on a 2-inch KTN crystal. The core and cladding layers were formed using liquid phase epitaxy. The cross-section and near-field pattern of the buried waveguide are shown in Fig. 1. We confirmed that the KTN waveguides were capable of singlemode beam propagation. The modefield diameter was about 7.6 µm for both the TE and TM modes. This core size provides us with a lower coupling loss between optical fibres and the KTN phase modulator than between optical fibres and a semiconductor modulator. We measured the propagation loss using optical low coherence reflectometry techniques and it was less than 0.5 dB/cm. We measured the polarisation-dependent loss (PDL) with a PDL meter (JDS Fitel PS3) and found it to be less than 0.1 dB/cm. This low PDL value results from the slight core ridge roughness generated during fabrication.

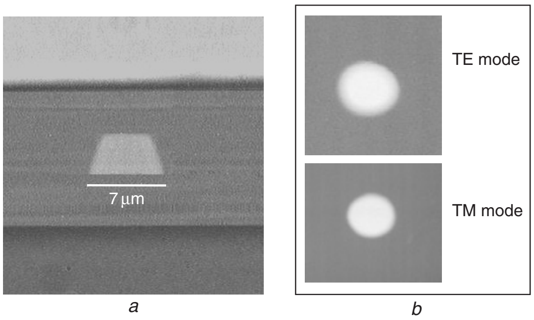

Fig. 1 *Cross-section of fabricated KTN buried waveguide, and near-field pattern of KTN buried waveguide*

a Cross-section of fabricated KTN buried waveguide
b Near-field pattern of KTN buried waveguide

We realised an EO phase modulator consisting of KTN waveguides by using retardation techniques. Fig. 2 shows the experimental setup. The polarised light, which was inclined at 45° to the optical axis of the KTN waveguide, was launched into the phase modulator using a polariser and PANDA fibre. The second polariser was positioned at the output. These two polarisers were arranged orthogonally in relation to each other to extinguish the input light. We detected the modulated output light intensity by supplying a voltage to the phase modulator.

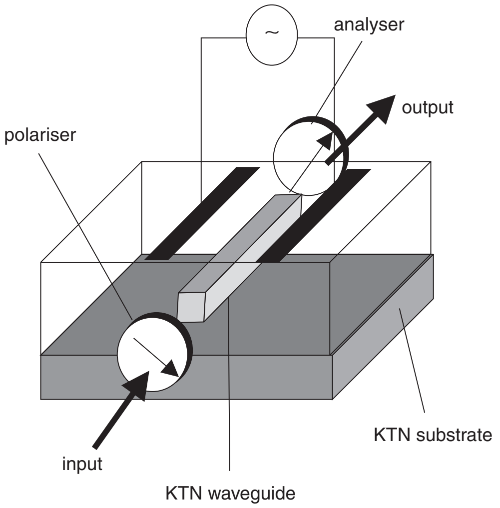

Fig. 2 *Experimental setup for realising EO phase modulators by retardation techniques*

Results and discussion: The output light was modulated in accordance with the following equation:

$$I_{out} = I_{in}(1 - \cos\phi) \tag{1}$$

Here, I_{in}, I_{out} and ϕ, respectively, are the input light intensity, output light intensity and retardation (phase difference between the TE and TM modes) caused by EO effects. The retardation ϕ in KTN crystals is expressed by the following equation:

$$\phi = -\frac{\pi}{\lambda_0} n_0^3 (s_{11} - s_{12}) \left(\frac{V}{d}\right)^2 l \tag{2}$$

Here, λ_0, n_0, V, d, l and s denote the input light wavelength, refractive index, applied voltage, electrode gap, electrode length and EO constant, respectively, and parameter s is expressed by the following equation:

$$s = g\varepsilon_0^2\varepsilon_r^2 \tag{3}$$

Here, g, ε_0 and ε_r denote a constant, the dielectric constant in a vacuum, and the dielectric constant in KTN crystals. The l and d values are 6 mm and 16 µm, respectively.

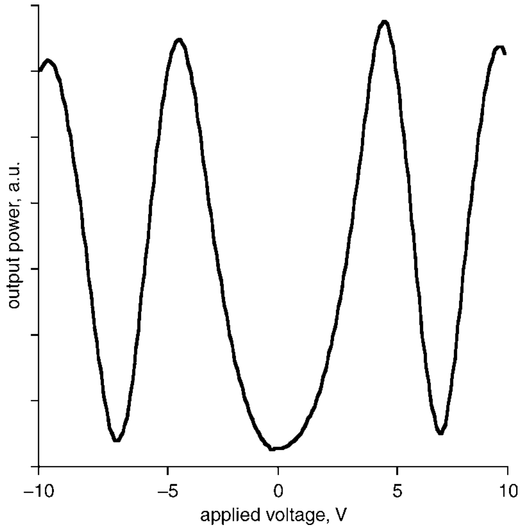

Fig. 3 *Optical output intensity against applied voltage*

Fig. 3 shows the optical output intensity against applied voltage. It is clearly seen that the output light modulation depends on the applied voltage. V_π is about 4.0 V. We can also find the local minimum around 6.5 V where the phase shift reaches 2π and the local maximum around 9.6 V where the phase shift reaches 3π. This means that the V_π value can be reduced to 2.5 V by applying a biased potential of 4.0 V in advance. The $V_\pi \times L$ value is an important performance index for optical phase modulators. The value of $V_\pi \times L$ is 1.5 cm V, which is less than one-third that of LN. Moreover, we estimated the electric field drop of the centre core to the surface electric field by using a static electric field calculation and found it to be about 0.34. The Kerr constant, $s_{11} - s_{12}$, is estimated to be 2.6×10^{-15} $(\mathrm{m/V})^2$ from (2), which is a value comparable to that of the bulk crystal [5]. These results suggest that an optimised electrode and waveguide configuration will lead to a further decrease in the $V_\pi \times L$ value (about 0.5 cm V). We then confirmed the fast response of the EO phase modulator. The rise time was 187 ps at 3 GHz, which is comparable to that of input electric signals. The modulation depth did not change between 1 and 3 GHz. This shows that KTN-based EO devices are useful for optical communication applications including transponders, packet switching and optical interconnection.

Conclusions: We successfully demonstrated an electro-optic (EO) phase modulator with a high performance index that uses newly developed $KTa_{1-x}Nb_xO_3$ (KTN) buried waveguides. The EO phase modulator had a low V_π value of less than 4.5 V. A 4.0 V biased potential resulted in phase modulator operation at below 2.5 V. The $V_\pi \times L$ value is 1.5 cm V, which is less than one-third that of LN. Moreover, the $V_\pi \times L$ value can be reduced to 0.5 cm V by optimising the electrode and waveguide configuration. The modulator also provided a fast response of 3 GHz. These results suggest that KTN waveguides will be very useful as fast electro-optic devices.

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