Nonlinear Cherenkov radiations modulated by mode dispersion in a Ti in-diffused LiNbO$_3$ planar waveguide

YAN CHEN, 1 ZHILIN YE, 1 YAODONG WU, 1 YUNFEI NIU, 1 RUI NI, 1 XIAOPENG HU, 1,* YONG ZHANG, 2 AND SHINING ZHU 1

1National Laboratory of Solid State Microstructures and School of Physics, Nanjing University, Nanjing 210093, China
2College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China
*xphu@nju.edu.cn

Abstract: We report nonlinear Cherenkov radiations (NCRs) in a Ti in-diffused LiNbO$_3$ planar waveguide. The radiations were modulated exploiting different polarizations and orders of the guided modes, the fundamental wavelengths and the working temperatures. Some characteristics related to NCRs, such as radiation angles and relative intensities were investigated in detail. The experimental results matched well with theoretical calculations.

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References and links

1. Introduction

When the velocity of a charged particle exceeds that of light in medium, coherent light would be emitted at a specific angle, which is called Cherenkov radiation in conventional particle physics [1]. Similar effect was applied to nonlinear optics as the nonlinear Cherenkov radiation (NCR), which requires that the phase velocity of the nonlinear polarization wave (NPW) exceeds that of the harmonic wave. NCR corresponds to an automatically accomplished phase-matching diagram, which means the Cherenkov phase matching angle will change accordingly to the varying of the parameters such as the input wavelength or the working temperature. NCR can be observed in both bulk ferroelectric crystals where the radiation is enhanced by the domain walls, and in nonlinear waveguides where the value of the momentum uncertainty in the thin film is more than the transverse momentum mismatch due to uncertainty principle [2, 3]. In both material platforms, several approaches can be exploited to modulate the behavior of NCRs. Forward and backward reciprocal vectors parallel to the direction of the NPW can deaccelerate or accelerate the phase velocity of the NPWs in periodically-poled nonlinear waveguides [4] or two-dimensional nonlinear photonic crystals [5, 6], thus changing of the radiation angles as well as the nonlinear conversion efficiencies. Besides, when the interacting waves are set to be at different polarization states, i.e., using the birefringence of ferroelectric crystals, the phase velocity of the NPW can be modulated as well. By this means, Cherenkov type second harmonic generation (SHG), was experimentally demonstrated in an anomalous dispersive ultra-thin MgO doped LiNbO$_3$ without phase velocity threshold [7]. Following the same idea, Cherenkov type different frequency generation (DFG), which cannot automatically be accomplished in normal dispersion materials, was realized in a KTP crystal [8]. In addition to utilizing the birefringence properties, the mode dispersion in waveguides can be engineered by choosing proper waveguide parameters, thus provide more flexibility in modulating NCRs. In this paper, we will report our results on NCR modulation in a Ti in-diffused LiNbO$_3$ planar waveguide by mode dispersion.

To fabricate optical waveguides in LiNbO$_3$, several methods, such as proton exchange, metal in-diffusion, femtosecond laser writing, ion implantation, optical grade dicing, and smart cut could be used [9, 10]. Here we chose Ti in-diffused LiNbO$_3$ waveguide to investigate NCRs, because both the ordinary and extraordinary refractive indices are increased after Ti in-diffusion, thus both TE and TM modes are supported in these waveguides. Moreover, the fabrication procedure is relatively simple.

For Cherenkov type SHG in waveguides, it is a guided-to-radiation nonlinear process, i.e., the fundamental wave (FW) is in the guided mode while the second harmonic (SH) wave is radiated into the substrate. In a $z$-cut, $x$-propagating Ti in-diffused LiNbO$_3$ waveguide, considering the non-zero elements of the second order nonlinear susceptibility of LiNbO$_3$, the $y$ and $z$-components of the second order nonlinear polarization $P_{2\omega}$ are given by [11]:

$$
P_y = 2\varepsilon_0 (d_{22}E_x^2 + 2d_{31}E_yE_z)$$

$$
P_z = 2\varepsilon_0 (d_{33}E_y^2 + d_{31}E_xE_z)$$

(1)

$E_y$ corresponds to the electric field of the TE mode and $E_z$ corresponds to that of the TM mode. Equation (1) contains four types of nonlinear processes, where the FWs take different waveguide modes and the radiated SH waves are of different polarizations. For simplicity, we adopt the notations which describe the nonlinear frequency conversions involving different polarizations in bulk crystals for the Cherenkov type SHGs: oo-o, eo-o, ee-e, and oo-e. It should be noted that ‘e’ is not exact for the SH wave, because there is a small angle, typically ten or more degrees, between the radiated SH wave and the $x$-axis of the crystal. The NCR’s phase-matching condition can be written as:
\[ \beta_i(\omega) + \beta_j(\omega) = k(2\omega) \cos(\theta) \]  

(2)

Where \( \beta_{ij}(\omega) = 2\pi \cdot Neff_{ij}(\omega) / \lambda(\omega) \), \( k(2\omega) = 2\pi \cdot n(2\omega) / \lambda(2\omega) \). \( Neff_{ij} \) denotes the effective refractive index of two guided modes at the FW, \( n \) is the refractive index of the SH wave in the substrate, and \( \theta \) is the internal Cherenkov angle. Equation (2) is satisfied only when the wave-vector mismatch \( \Delta k = \beta_i(\omega) + \beta_j(\omega) - k(2\omega) \) is less than zero. The cladding layer of Ti in-diffused LiNbO\(_3\) waveguide is the air, while the refractive index of the guided layer is around 2.2, so Cherenkov SH waves can only radiate into the substrate, instead of into the air, due to the phase-matching requirement.

The refractive index profile of a Ti in-diffused LiNbO\(_3\) planar waveguide is determined by the thickness of the Ti film, the diffusion temperature and the diffusion time. After the waveguides have been fabricated at certain process parameters, NCRs could be modulated by changing the working temperature, the input wavelength and exploiting different modes involved in the nonlinear interactions.

The waveguide used in our experiment was fabricated by Ti in-diffusion. A sample with dimensions 20 \( \times \) 10 \( \times \) 0.5 mm\(^3\) along X, Y, Z axes was prepared from a congruent LiNbO\(_3\) wafer. After cleaning, an 80-nm thick Ti layer was deposited on the \(-z\) face of the sample by electron-beam evaporation. Then Ti in-diffusion was carried out at 1050 °C for 9 hours in air ambient. The end facets of the waveguide were polished for optical measurements. Subsequently, the effective refractive index was characterized through a prism coupler at 632.8 nm. With the inverse WKB analysis [12], the diffusion depth was fitted to be 4.03 \( \mu \)m, thus we could obtain the refractive index profiles at different wavelengths according to [13–15]. We calculated the mode dispersion by the WKB analysis [16], finding four guided modes (TM0, TM1, TE0 and TE1) were supported at 1064 nm, while three modes (TM0, TM1 and TE0) were supported at the longer wavelength of 1342nm in this waveguide. Figure 1(a) shows the temperature dependent dispersion relations of the FW at 1064 nm and the SH wave at 532 nm. It is evident that for ee-e, oo-o, and eo-o processes, Eq. (2) is automatically completed since the relation \( n(2\omega) > Neff_{ij}(\omega) \) is always satisfied. While for the oo-e process, as shown in Fig. 1(b), NCR is phase-matched at the temperatures above 70°C when the FW is in the TE0 mode, while the critical phase-matching temperature goes down to 20°C when the FW is in the TE1 mode.
2. Experimental setup

The schematic experimental setup is shown in Fig. 3. The fundamental source is a Q-switched Nd:YVO₄ laser operating at 1064nm/1342nm with a pulse width of 20ns/30ns and a repetition rate of 10 kHz. The polarization of the near infrared beam was controlled by a half wave plate and was focused into the planar waveguide through a cylindrical lens with a 5-mm focal length. The waveguide was put in an oven for accurate temperature control. The generated NCRs were displayed on a screen which was placed 85 mm away from the end facet of the sample. Normally, one can observe two groups of SH spots symmetrically displayed on both sides of the horizontal line of the waveguide, and it can be explained as the following. Because the internal radiation angles are normally less than 20°, so part of the SH waves will experience multiple total internal reflections in the LiNbO₃ substrate and exit from the end facet of the waveguide, see the inset in Fig. 3. The lower spots on the screen came from the SH waves directly hitting the end facet, as well as the ones last reflected at the upper surface of the substrate before hitting the end facet of the waveguide. While the upper spots came from the SH waves last reflected from the lower surface of the substrate.

3. Results and discussions

Firstly, the FW was chosen to be at 1064 nm with 45-degree polarization and the temperature of the waveguide was set to 50°C. Four groups of NCRs should be observed in total, which corresponded to the four processes utilizing different nonlinear coefficients described in Eq. (1). As shown in left part of Fig. 4, group ⊁, ⊂ and ⊄ can be clearly observed and each group of radiations included two or more Cherenkov radiation spots, which were attributed to Cherenkov SHG or sum frequency generation (SFG) between different guided modes. Group ⊁ and ⊂ were Cherenkov type frequency up-conversions via the oo-e and ee-e process,
where the FWs in each group were in the waveguide modes with same polarization but different orders. As for group ④, the spots therein were eo-o type Cherenkov SFGs between different order TE and TM modes. The radiations in Group ④ through the oo-o process were much weaker than the radiations in group ②, which can be seen from the relative output intensities in Table 1. In experiment, to obtain a suitable contrast ratio between group ④ and ② which were close to each other, we set the polarization of the FW to be mainly at the horizontal, thus group ④ could be visualized as shown in the middle part of Fig. 4.

Figure 5 shows the behavior of the oo-e type NCR at different temperatures. There was only one pair of spots induced by Cherenkov SHG of the FW in the TE1 mode at 25°C, between which was a bright spot generated from the collinear guided-to-guided SHG process. When the temperature was increased to 50°C, a new pair of spots appeared, which were generated through Cherenkov SFG of the TE1 and TE0 modes. Meanwhile, the collinear SHG spot weakened obviously because the working temperature was far from the collinear phase-matching temperature at about 20°C. When the temperature was further increased to 75°C, the phase-matching condition for Cherenkov SHG of the FW in the TE0 mode was satisfied, which was consistent with our predictions in Fig. 1(b).

The measured external radiation angles varying with the working temperature of the waveguide was given in Fig. 6. With temperature increasing, the radiation angles of the oo-e process became larger, while for ee-e, eo-o, and oo-o processes the radiation angles remained
almost the same because temperature has little influence on the wave-vector mismatches for the three processes.

![Graph showing temperature vs. external NCR angles](image)

Fig. 6. Experimental (the circle) and theoretical (the line) external radiation angles varying with temperatures for different types of NCRs.

In order to investigate the behavior of the NCRs in the Ti in-diffused waveguide at different wavelengths, we changed the incident light to a nanosecond pulsed 1342 nm laser. Then three kinds of radiation spots was observed, as shown in Fig. 7, when the input beam was 45° polarized. Group ①, ② and ③ were obtained through eo-o, oo-o and ee-e type NCRs respectively. The number of radiation spots in each group was determined by the guided mode supported at 1342 nm, where were TE0, TM0 and TM1 as mentioned previously. The external NCR angles of the ee-e, oo-o and eo-o processes, where the FW only took the lowest order guided modes, were measured to be 26.3°, 29.7° and 39.5°, which matched well with the calculated values 26.0°, 29.7° and 39.0°, respectively. In experiment, oo-e type NCR could not be observed in the temperature range from 25 °C to 200 °C, which was consistent with the theoretical predictions in Fig. 2.

![Groups of NCRs at 1342nm](image)

Fig. 7. Three groups of NCRs at the fundamental wavelength of 1342nm were shown in the left part. Right part is the zoom in view of the radiation spots in group ② and ③. The guide modes involved are indicated beside the radiation spots.

We also investigated the efficiencies of the NCRs. By applying the nonlinear coupled-mode theory [17], the output power of the NCRs can be written as:

\[
P_{SH} \propto P_{FW}^2 \left[ \frac{\omega^2 d^{(2)}}{\beta_{SH}} \cdot S \right]^2 \cdot \frac{1}{\tan \theta}
\]

(3)

where \( P_{FW} \) is the power of the FW coupled into the waveguide, \( \beta_{SH} \) is the propagation constant of the SH wave, \( d^{(2)} \) denotes the second order nonlinear coefficient. \( S \) is the
normalized overlap integral between the FW and SH electromagnetic field. Assuming \( P_{yw} \) to be the same, we can calculate the relative radiation intensities for different processes at 50 °C. As shown in Table 1, oo-e type NCR at 1064 nm has the most intense SH output, which has a small radiation angle and a large overlap integral due to small phase mismatch, though the nonlinear coefficient for this process is not the biggest. The output of the two ee-e processes were less intense, which utilizes the largest nonlinear coefficient. As for oo-o and eo-o processes, the small nonlinear coefficients, small overlap integrals and large radiation angles lead to far less SH powers than the former two processes. Calculations were in good accordance with the experimental observations.

<table>
<thead>
<tr>
<th>Type of NCR</th>
<th>Wavelength (nm)</th>
<th>( d_{13} ) (pm/V)</th>
<th>( S(V^2/A/m^2) )</th>
<th>( 1/\tan \theta )</th>
<th>Normalized Intensity (a.u.)</th>
</tr>
</thead>
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<tr>
<td>ee-e</td>
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<td>27</td>
<td>0.038</td>
<td>3.97</td>
<td>1.000</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.093</td>
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</tr>
<tr>
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</tr>
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</table>

4. Conclusions

Ti in-diffused LiNbO\(_3\) is a promising platform for integrated nonlinear photonics, and in this paper, a comprehensive theoretical and experimental study on NCRs in a Ti in-diffused LiNbO\(_3\) planar waveguide was presented. The mode dispersions were numerically calculated to find out the phase-matching requirements for NCRs. In experiment, we observed rich phenomena of NCRs which were realized through Cherenkov type second harmonic generation of the same guided mode as well as sum frequency generation between guided modes with different polarizations and different orders. The dependence of the radiations on the wavelength of the input FW and the working temperature were also studied and experimentally confirmed. The relative output intensity of the radiations were mainly determined by the second-order nonlinear coefficient, the overlapping integral and the radiation angle, and the numerical results were consistent with experimental observations. The phase-matching conditions required in this work are for Cherenkov type frequency up-conversions. When the requirements are not satisfied, for example, below some critical temperatures in Fig. 1(b), Cherenkov type frequency down-conversions could be realized. Thus, Cherenkov type different frequency generations (DFG) and spontaneous parametric down conversions (SPDC) based on mode dispersion tailoring might be further research topics in Ti in-diffused LiNbO\(_3\) waveguides, which would provide compact tunable laser light sources and entangled photon sources respectively.

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