Tuning characteristics of narrowband THz radiation generated via optical rectification in periodically poled lithium niobate

C. Weiss, G. Torosyan, J.-P. Meyn, R. Wallenstein and R. Beigang
Fachbereich Physik, Universitaet Kaiserslautern, Erwin-Schroedinger-Str, 67663 Kaiserslautern, Germany
beigang@physik.uni-kl.de

Y. Avetisyan
Microwave Engineering Department, Yerevan State University, 1 Alek Manoogian Str.,375049 Yerevan, Armenia
gerbarcr@ysu.am

Abstract: The tuning properties of pulsed narrowband THz radiation generated via optical rectification in periodically poled lithium niobate have been investigated. Using a disk-shaped periodically poled crystal tuning was easily accomplished by rotating the crystal around its axis and observing the generated THz radiation in forward direction. In this way no beam deflection during tuning was observed. The total tuning range extended from 180 GHz up to 830 GHz and was limited by the poling period of 127 µm which determines the maximum THz frequency in forward direction.

© 2001 Optical Society of America
OCIS codes: (190.4360) Nonlinear optics, devices ; (320.7110) Ultrafast nonlinear optics

References and links

1. Introduction

The generation of ultrashort pulses in the THz frequency range via transient photoconductivity or optical rectification using femtosecond laser pulses in the near infrared spectral region is a well established technique [1-3]. Single cycle pulses centered around 1 THz with bandwidths extending up to several ten THz have been observed [4, 5]. Recently,
the generation of narrowband THz radiation using optical rectification in periodically poled lithium niobate (PPLN) has been reported \[6 – 8\].

An ultrashort pulse traveling through a PPLN crystal (see Fig. 1) generates a nonlinear polarization via difference frequency generation between the spectral components of the ultrashort laser pulse. To make use of the highest nonlinear coefficient $d_{33}$, the laser beam is polarized along the z-axis and the difference frequency polarized along the z-direction will be detected. For both waves, the extraordinary indices of refraction have to be used in this configuration. The nonlinear polarization along the z-axis of the PPLN will be induced according to \[9\]:

$$P_{NL}^z = d(x) \cdot E^2 \cdot f(y, z) \cdot g(t - \frac{x}{v_g}).$$ \hspace{1cm} (1)

Here $d(x)$ is the nonlinear coefficient with the magnitude $d_{33}$ and alternating sign in each domain. $E$ is the amplitude of the lasers electric field, $f(y,z)$ is the spatial intensity distribution of the laser in y- and z-direction, $v_g$ is the group velocity of the pump beam and $g(t)$ describes the temporal intensity profile of the pulse. The polarization gives rise to emission of a narrowband coherent THz radiation if the number of poled periods is large enough.

According to \[9\] the frequency $\Omega$ of the generated THz radiation is determined by the poling period $\Lambda$, the indices of refraction $n_{THz}$ and $n_{IR}$ of the THz and IR beam and the internal direction of emission $\Phi$ (see Fig. 1), respectively. The dependence of the generated THz frequency as a function of the emission angle is given by equation (2) and shown in Fig. 2.

$$\Omega = \frac{c}{\Lambda} \cdot \frac{1}{n_{IR} - n_{THz} \cdot \sin \Phi}$$ \hspace{1cm} (2)

Fig. 1. Schematic diagram of the PPLN crystal for THz-generation

Fig. 2. Frequency of the generated THz radiation as a function of observation angle for a poling period $\Lambda = 127 \mu$m
For $\Phi = \pm 90^\circ$ THz radiation in forward and backward direction can be observed [6]. The possibility to observe THz radiation in other directions ($\Phi = \pm 90^\circ$) is caused by the fact that the pump beam is focused to a small beam waist [9].

Observation of the THz radiation emitted in the direction $\Phi = 0^\circ$ has the advantage that the absorption length in the PPLN crystal is reduced considerably and the area of THz emission is increased leading to a smaller beam divergence. Details about this type of generation are reported in [9]. Here we discuss the tuning properties for generation in forward direction.

2. Experimental set-up

Tuning of the THz wavelength can easily be accomplished by changing the poling period of the PPLN crystal. This can be done using segments of the crystal with different poling periods. But in this case tuning is not continuous. Another possibility is to change the effective poling period by changing the orientation of the poled periods. This can easily be accomplished by rotating a circular PPLN crystal (see Fig. 3). The pump beam passes through the center of the crystal (which is also the axis of rotation) so that the beam direction stays constant during rotation of the crystal. In this way any beam deviation during rotation can be avoided.

The effective poling period changes with $1/\cos \alpha$ where $\alpha$ is the angle between the direction of beam propagation and the normal to the poling direction and therefore the center frequency of the THz radiation generated in forward direction is given by:

$$\Omega = \frac{c \cos \alpha}{\Lambda} \cdot \frac{1}{n_{\text{IR}} - n_{\text{THz}}}$$

(3)

This formula is correct only if the angle $\alpha$ is small compared to $90^\circ$, i.e. if the number of participating segments of the PPLN crystal is large enough. For $\alpha = 90^\circ$ there are no poled segments for the propagating fs pulse.

There is a phase delay across the THz beam profile, when the domain interface is not perpendicular to the direction of the pump beam. This phase delay can be neglected, if the diameter of the pump beam is significantly smaller than the poling period.

The maximum frequency is obtained for $\alpha = 0^\circ$ and determined by the poling period. It is only limited by the bandwidth of the Ti:sapphire pump pulses. For our PPLN crystal with a poling period of 127 $\mu$m the maximum frequency was 0.826 THz. For a pulse length of 100 fs and sech²-shaped Fourier limited pulses a maximum THz frequency of 3.15 THz can be expected using a poling period of approximately 35 $\mu$m. It should be pointed out that at higher frequencies the strong absorption of lithium niobate [10] due to a lattice resonance limits the
use of this material for optical rectification at room temperature with periodically poled structures. For THz frequencies above 3 THz a surface-emitting geometry is preferable [9].

Our experimental set-up is shown in Fig. 4. It consists of a 100 fs Ti:sapphire laser operating at 780 nm with a repetition rate of 82 MHz and an average output power of up to 1.5 W. The PPLN crystal is placed in the focal point of the near infrared beam which is focused to a beam waist of ~10 µm. The PPLN crystal had a diameter of 7.5 mm and a poling period of 127 µm. The generated THz radiation was collected in the direction of the pump beam with an off-axis parabolic mirror. A conventional THz detection system using a fast silicon-on-sapphire (SOS) photoconductive switch was applied to detect the THz radiation.

![Fig. 4. Experimental set-up for THz generation in forward direction](image)

**3. Pulse shape and tuning properties**

A typical temporal pulse shape measured with our experimental set-up in forward direction is shown in Fig. 5.

![Fig. 5. Temporal pulse shape observed in forward direction](image)

The decay of the electric field strength is caused by the strong absorption in the PPLN crystal. As a consequence, the effective crystal length used for THz generation is limited to approximately 4.5 mm corresponding to 35 poled periods.
We have investigated the tuning properties in forward direction. By rotating the crystal the THz frequency was tuned from 180 GHz to 830 GHz. The tuning characteristic follows equation (3) as can be seen in the upper part of Fig. 6. There was no beam displacement during tuning within our experimental accuracy.

![Fig. 6: THz frequency observed in forward direction as a function of angle between the direction of propagation and poling (upper diagram). The solid line represents the theoretically obtained tuning characteristics. The lower diagram shows the relative bandwidth for different propagation angles. The solid line represents the calculated relative bandwidth, assuming a rectangular waveform and therefore neglecting the absorption effects.](image)

Fig. 7 shows the corresponding spectral amplitude of the waveform measured for an angle of $\alpha = 0^\circ$. In addition to the frequency generated in forward direction the backward radiation at 320 GHz is clearly resolved. This signal is caused by a reflection of the backward generated wave at the entrance surface of the PPLN crystal.

According to theory we also expect frequency components corresponding to higher order quasi-phase-matching. However, we did not observe these frequency components in this particular case due to the spectral response of our detection system and the reduced amplitude of the radiation in higher orders. For larger poling periods, quasi-phase-matching in third order was observed and will be presented in [11].

The tuning behavior as a function of angle can be animated in Fig. 7 for typical experimental results, where the amplitude spectrum of the generated frequency is shown as a function of the rotation angle indicated in the inset of the figure. Together with a shift of the center frequency an increase in bandwidth can be observed. This behavior can be explained in terms of the decreasing number of poled periods involved in the generation process during tuning.

The bandwidth of the THz pulse depends on the number $N$ of poled periods used for generation and the envelope of the temporal waveform. The relative bandwidth is given by [9]

$$\left(\frac{\Delta\Omega}{\Omega}\right)_\lambda = \frac{C}{N},$$

where the constant $C$ depends on the temporal waveform. For a rectangular envelope we obtain $C = 1.2$. Simultaneously with the increase of the poling period with propagation angle the number of poled periods involved in the generation process decreases proportional to $\cos \alpha$. As a consequence the bandwidth will increase with increasing angle.
The calculated relative bandwidth in forward direction for our crystal is shown in the lower part of Fig. 6 as solid line graph, assuming a rectangular temporal pulse envelope and no absorption. The smallest relative bandwidth is $\Delta \Omega / \Omega = 0.021$, which corresponds to a bandwidth of 17.5 GHz for a propagation angle of $\alpha = 0^\circ$.

The corresponding experimentally determined bandwidth is also shown in the lower part of Fig. 6. The measured relative bandwidth of 0.026 and the dependence on the propagation angle are in good agreement with the calculations taking into account that the effective length of the crystal is reduced by absorption and that the pulse envelope is not rectangular. A detailed analysis of the temporal and spectral waveform will be given elsewhere [11].

![Fig. 7. Spectral amplitude obtained from the experimental observed waveform (Movie, 1.5 MB).](image)

**4. Summary**

In summary we have demonstrated the tuning capabilities of narrowband THz radiation generated via optical rectification of 100 fs long pulses from a mode locked Ti:sapphire laser in periodically poled lithium niobate. Continuous tuning without beam displacement was accomplished by rotating a disk shaped PPLN crystal around the center of the crystal. The tuning range extended from 180 GHz to 830 GHz and was limited in our experiment by the poling period of 127 µm. In principle, the maximum frequency is only limited by the available bandwidth from the near infrared pump pulses. The bandwidth of the THz pulses was mainly determined by the number of poled periods, which contribute to the generation process, which, in turn, was limited by the strong absorption of the PPLN crystal at the THz wavelengths generated.