# Unidirectional radiation of widely tunable THz wave using a prism coupler under noncollinear phase matching condition 

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#### Abstract

A widely tunable THz wave has been parametrically generated and reported recently by us utilizing a $\mathrm{LiNbO}_{3}$ crystal with a monolithic grating coupler under a noncollinear phase matching condition. However, the output direction of the THz wave is strongly dependent on the generated frequency due to the nature of noncollinear phase matching, as well as the grating coupler. In this letter, a novel method for THz coupling is proposed using a low dispersion prism to eliminate almost completely the THz beam deflection for the entire tuning range. The unidirectional THz wave radiation was confirmed theoretically and experimentally for the range of $1-2 \mathrm{THz}$. © 1997 American Institute of Physics. [S0003-6951(97)02632-6]


Over the last decade, several techniques involving the use of photoconductivity and optical rectification have been developed for the THz radiation. ${ }^{1-4}$ Most studies have utilized ultra-broad-bandwidth characteristics of femtosecond optical pulses, so that the generated THz waves possess high temporal characteristics with the sacrifice of their temporal coherence.

In contrast to these methods, we have recently demonstrated a room temperature operated tunable THz-wave generation introducing a monolithic grating coupler onto a $\mathrm{LiNbO}_{3}$ crystal which was pumped by a $Q$-switched Nd:YAG laser. ${ }^{5,6}$ The process involved is an optical parametric oscillation (OPO) utilizing the polariton mode scattering of $\mathrm{LiNbO}_{3}$ based on the $248 \mathrm{~cm}^{-1} A_{1}$-symmetry soft mode. ${ }^{7}$ Idler (near-infrared) and THz waves are parametrically generated by the pump, and three wave vectors $\left(\mathbf{k}_{p}, \mathbf{k}_{i}, \mathbf{k}_{T} ; p:\right.$ pump, $i:$ idler, $T: \mathrm{THz}$ ) are noncollinearly phase matched (NCPM) as shown in the inset of Fig. 1. The generated wavelength of idler $\left(\lambda_{i}\right)$ is a few nanometers longer than the pump wavelength $\left(\lambda_{p}=1.064 \mu \mathrm{~m}\right)$, and that of the THz wave $\left(\lambda_{T}\right)$ is more than a hundred times longer than $\lambda_{p}$, so that the wave vectors have a relation $\left|\mathbf{k}_{p}\right|>\left|\mathbf{k}_{i}\right|$ $\gg\left|\mathbf{k}_{T}\right|$. Consequently, the angle $\phi$ between the pump wave and the idler wave is small $\left(\sim 0.8^{\circ}\right)$, and the angle $\delta$ between the idler and the THz wave is relatively large $\left(\sim 65^{\circ}\right)$. Tunability $\left(\lambda_{T}=150-290 \mu \mathrm{~m}\right)$ is obtained by changing the angle $\phi$ between the pump and the idler. As the NCPM condition changes for the tuning, the direction angle $\delta$ of the generated THz wave inside the crystal changes. Furthermore, the THz wave suffers total internal reflection at the crystalair interface due to a large refractive index of nonlinear crystals in the THz -wave region $\left(\sim 5.2\right.$ for $\left.\mathrm{LiNbO}_{3}\right)$.

In the former experiments, two types of specially prepared crystals were used to avoid the total internal reflection. One was with a cut exit at the corner of the crystal so that the THz wave emerges approximately normal to the exit surface ${ }^{7}$ (angled surface coupler: ASC). Another type was with a monolithic grating coupler (GC) fabricated on the crystal surface using a precise dicing saw. ${ }^{5,6}$ For ASC, refractive

[^0]index dispersion of the nonlinear material (e.g., $\mathrm{LiNbO}_{3}$ ) and the change of the phase-matching angle $\delta$ directly influence the output direction $\theta_{\text {air }}$. For GC, the output direction change is relatively large due to the Bragg condition and the wide tuning range of the THz wave. The average rates of these radiation angles change around $\lambda_{T} \approx 200 \mu \mathrm{~m}$ for both methods are
\[

$$
\begin{align*}
& \left(\frac{\Delta \theta_{\text {air }}}{\Delta \lambda}\right)^{\mathrm{ASC}} \approx-0.017(\mathrm{deg} . / \mu \mathrm{m})  \tag{1}\\
& \left(\frac{\Delta \theta_{\text {air }}}{\Delta \lambda}\right)^{\mathrm{GC}} \approx 0.65(\operatorname{deg} . / \mu \mathrm{m}) \tag{2}
\end{align*}
$$
\]

The stable output direction of the THz wave is usually desirable for many applications. Here we report a new method to fix the THz-wave direction by employing a semiconductor prism coupler (PC) sitting on the $y$ surface of the $\mathrm{LiNbO}_{3}$ as shown in Fig. 1. Inside the nonlinear crystal, the angle between the pump and the idler waves depicted in Fig. 1 is given by

$$
\begin{align*}
\cos \phi\left(\cong 1-\frac{1}{2} \sin ^{2} \phi\right) & =\frac{\left|\mathbf{k}_{p}\right|^{2}+\left|\mathbf{k}_{i}\right|^{2}-\left|\mathbf{k}_{T}\right|^{2}}{2\left|k_{p}\right|\left|k_{i}\right|} \\
& =\frac{n_{p}^{2} v_{p}^{2}+n_{i}^{2} v_{i}^{2}-n_{T}^{2} v_{T}^{2}}{2 n_{p} v_{p} n_{i} v_{i}} \tag{3}
\end{align*}
$$

where $v_{j}$ and $n_{j}(j=p, i, T)$ are frequencies and refractive indices for $\lambda_{j}$, respectively, satisfying the energy conserva-


FIG. 1. Experimental cavity arrangement of unidirectional THz wave radiation using Si-prism coupler. The change of the angle $\theta$ is $\cong 0.01^{\circ}$, though the angle $\delta$ varies up to $\cong 1^{\circ}$ as the THz wavelengths are tuned from 150 to 290 $\mu \mathrm{m}$.
tion law of $v_{p}=v_{i}+v_{T}$. We can assume that $n_{p} \approx n_{i}$ and $\theta \ll 1$, since $v_{p} \leqslant v_{i}>v_{T}$ for the parametric THz-wave generation. From Eq. (3), we have

$$
\begin{equation*}
\sin \phi=v_{T} \sqrt{n_{T}^{2}-n_{p}^{2}} / v_{p} n_{p} . \tag{4}
\end{equation*}
$$

According to Eq. (4) and the wave vectors in Fig. 1, $\delta$ can be expressed by a simple form as

$$
\begin{equation*}
\sin \delta=\left(n_{p} v_{p} / n_{T} v_{T}\right) \sin \phi=\sqrt{n_{T}^{2}-n_{p}^{2}} / n_{T} \tag{5}
\end{equation*}
$$

so that

$$
\begin{equation*}
\delta=\cos ^{-1}\left(n_{p} / n_{T}\right) \quad\left(n_{p}=\text { fixed value }\right) \tag{6}
\end{equation*}
$$

In Eq. (6), $\delta$ changes as the THz wavelength is tuned due to the large dispersion of the nonlinear crystal in the THz-wave region.

The angle $\theta$ of the THz-wave inside the prism is directly related to the angle $\delta$ by Snell's law; $n_{T} \cos \delta=n_{T}^{c} \cos \theta$, where $n_{T}^{c}$ is the refractive index of the prism for the THz wave. From Eq. (6), we obtain

$$
\begin{equation*}
\theta=\cos ^{-1}\left(n_{p} / n_{T}^{c}\right) \quad\left(n_{p}=\text { fixed value }\right) \tag{7}
\end{equation*}
$$

In the derivation of Eq. (7), it is most important to note that $n_{T}$ cancels between Eq. (6) and Snell's law. This happens only when the crystal-prism interface is parallel to the idler wave (i.e., resonator axis). From Eq. (7), it is clear that $\theta$ is affected only by $n_{T}^{c}$. Required features of the prism are, therefore, (a) low dispersion of $n_{T}^{c}$; (b) $n_{T}>n_{T}^{c}>1$ in order to avoid total internal reflection; and (c) low absorption. High resistivity Si is a low absorption material and is commonly used for THz optics. In addition, the dispersion of Si around $\lambda_{T} \approx 200 \mu \mathrm{~m}$ is $\Delta n_{T}^{c} / \Delta \lambda_{T}=-1.67 \times 10^{-5}\left(\mu \mathrm{~m}^{-1}\right)$ while that of $\mathrm{LiNbO}_{3}$ is $-3.06 \times 10^{-3}\left(\mu \mathrm{~m}^{-1}\right)$. Hence, high resistivity Si is one of the best materials for the PC method.

Assuming a Si prism sitting on a $\mathrm{LiNbO}_{3}$ crystal, calculated angle changes of $\delta, \theta$, and $\theta_{\text {air }}$ for the whole tuning range $(150-290 \mu \mathrm{~m})$ are $\Delta \delta=0.9^{\circ}, \Delta \theta=0.01^{\circ}$, and $\Delta \theta_{\text {air }}$ $=0.03^{\circ}$, respectively, and the averaged rate of the radiation angle change around $\lambda_{T} \approx 200 \mu \mathrm{~m}$ is

$$
\begin{equation*}
\left(\frac{\Delta \theta_{\text {air }}}{\Delta \lambda}\right)^{\mathrm{PC}} \approx-0.00018(\operatorname{deg} . / \mu \mathrm{m}) \tag{8}
\end{equation*}
$$

The change of radiation angle reduces to $1 / 95$ in comparison with the ASC method [Eq. (1)], and reduces to $1 / 3600$ compared with the GC method [Eq. (2)]. The radiation angle changes of the THz wave are shown in Fig. 2 for ASC, GC, and $\mathrm{Si}-\mathrm{PC}$. Here, the change of the radiation angle is set to be zero at $\lambda_{T}=200 \mu \mathrm{~m}$ as a reference. In the case of ASC, the radiation angle outside the crystal varies up to $4^{\circ}$ according to Snell's law with $0.9^{\circ}$ change of $\delta$ inside the crystal, due to the large refractive index $\left(n_{T}>5\right)$ of $\mathrm{LiNbO}_{3}$. In the case of GC, the radiation angle varies as much as $100^{\circ}$ mainly due to the Bragg condition. On the contrary, the change of the radiation angle is only $0.03^{\circ}$ for $\mathrm{Si}-\mathrm{PC}$, proving this method to be far more convenient than ASC or GC. More noteworthy is the fact that this method applies to any THz-wave generation from an optical wave using NCPM condition whether it is a parametric oscillation or a difference frequency generation, regardless of the kinds of nonlinear crystals or prism materials.


FIG. 2. Calculated radiation angle changes for three different THz coupling methods; angled surface coupler, grating coupler, and prism coupler. Changes of radiation angle are set to be zero at $\lambda_{T}=200 \mu \mathrm{~m}$ for comparison.

In order to verify the unidirectional THz -wave radiation, an experiment was performed as shown in Fig. 1. A 5-mmthick $\mathrm{LiNbO}_{3} z$ plate was cut to a dimension of $70(x)$ $\times 10(y) \times 5(z)\left(\mathrm{mm}^{3}\right)$. Two end surfaces in the $x$ plane were cut parallel, polished, and antireflection (AR) coated for operation at $1.07 \mu \mathrm{~m}$. The $y$ surface was also polished flat in order to minimize the coupling gap between the prism base and the crystal surface. High resistivity $\operatorname{Si}(\rho>1000 \Omega \mathrm{~cm}$, $\alpha \cong 0.6 \mathrm{~cm}^{-1}$ ) was chosen for fabricating the prism. The Si prism was prepared with a length of 10 mm along the base, and a prism angle of $39^{\circ}$ so that the THz wave would emerge normal to the prism exit surface. The prism base was slightly pressed with an adjustable spring against the $\mathrm{LiNbO}_{3}$ crystal to maximize the coupling efficiency. The crystal with the prism was placed inside the cavity which was resonated by the idler wave using two high-reflection mirrors, M1 and M2. Both mirrors were half-area coated, so that only the idler wave could resonate and the pump beam propagate through the uncoated area without scattering. The pump source used was a $Q$-switched Nd:YAG laser whose electric field was along the $z$ axis of the $\mathrm{LiNbO}_{3}$ crystal. The pump power, pulsewidth, and repetition rate were $30 \mathrm{~mJ} /$ pulse, 25 nsec , 16.7 Hz , respectively. The pump beam entered the $x$ surface of the crystal and traversed the $\mathrm{LiNbO}_{3}$ crystal in proximity to the $y$ surface. By varying the incident angle of the pump beam from $1^{\circ}$ to $2^{\circ}$ the angle $\phi$ between the pump and idler inside the crystal was changed from $\sim 0.5^{\circ}$ to $1^{\circ}$. As the plane matching angle was tuned, the idler and the THz wavelengths varied from 1.068 to $1.072 \mu \mathrm{~m}$ and 290 to $150 \mu \mathrm{~m}$, respectively. The angle $\delta$ between the idler and THz wave inside the crystal changed from $64.9^{\circ}$ to $65.8^{\circ}$.

The observed THz-wave beam was directed to $\theta_{\text {air }}$ $=51^{\circ}$, and had an approximately Gaussian cross section with an $e^{-2}$ power radius of 5 mm at the distance of 50 cm away from PC. A $5 \mathrm{~mm} \phi$ aperture was fixed at this position as a spatial filter, and a 4.2 K Si bolometer was placed behind the aperture to detect the transmitted THz wave. The power and the pulsewidth of the THz wave were measured to be $30 \mathrm{pJ} /$ pulse ( 3 mW , peak) and 10 ns , respectively. Here, the pulsewidth of the THz wave was monitored by a Schottky barrier diode (SBD). ${ }^{8}$ The measured direction angle


FIG. 3. Measured THz wave intensity dependence on the wavelength for prism coupler (solid line) and angled surface coupler (stars). In the case of the prism coupler, the bolometer position was fixed, meanwhile, in the case of angled surface coupler, the bolometer position had to be shifted point to point each time to measure, since the radiation angle varied as tuned.
$\theta_{\text {air }}$ agreed well with the theoretical value $\left(\theta=51^{\circ}\right)$ given by Eq. (7) provided $n_{p}=2.15\left(\mathrm{LiNbO}_{3}\right.$ for $\left.\lambda_{p}=1.064 \mu \mathrm{~m}\right)$, $n_{T}^{c}=3.42\left(\mathrm{Si}\right.$ for $\left.\lambda_{T}=150-290 \mu \mathrm{~m}\right)$. The tuning range of the THz wave was measured to be $150-290 \mu \mathrm{~m}$ using the $\mathrm{Si}-\mathrm{PC}$ as the solid line shown in Fig. 3. In the figure, stars ( $*$ ) indicate the data obtained by the ASC method, i.e., a cut exit at the end corner of the $\mathrm{LiNbO}_{3}$ crystal. In the case of the ASC method, the bolometer position had to be shifted point to point each time to measure, since the radiation angle varied as it tuned. By comparing the tuning ranges of both methods, the radiation direction $\theta_{\text {air }}$ was assured to be constant by the use of Si-PC. It follows from what has been said that the radiation angle $\theta_{\text {air }}$ of the wide tunable THz wave was fixed when coupled out of the nonlinear crystal surface
which was parallel to the idler wave utilizing a lowdispersive PC.

In conclusion, we have demonstrated theoretically and experimentally a new method of unidirectional THz-wave radiation using a prism coupler. Our THz-wave source is expected to play an important role in various application fields such as THz spectroscopy or THz imaging, using this unique property of unidirectional radiation.

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