During the past several years, THz-wave generation and detection have attracted much attention from both the fundamental and applied points of view. Most studies have utilized ultrabroad bandwidth characteristics of femtosecond optical pulses based on recent progress in laser technology, so that the generated THz waves possess high temporal characteristics with the sacrifice of their temporal coherence.1–4

In contrast to recent studies, many research efforts had been carried out a couple of decades ago concerning the generation of tunable coherent far-infrared radiation based on optical technology.5–9 Among them the efficient and wide tunable THz generation had been reported in the pioneering works of Pantell, Puthof, and others in the late 1960s to early 1970s.7–9 This is based upon tunable light scattering from the 

\[ \text{long-wavelength side of the} \]

\[ \text{1-symmetry soft mode in} \]

\[ \text{LiNbO}_3. \]

The input (pump) photon at near-infrared stimulates a near-infrared Stokes photon (called an ‘‘idler’’ in this letter) at the difference frequency between the pump photon and the vibrational mode. At the same time, the THz wave (signal) is generated by the parametric process due to the nonlinearity arising from both electronic and vibrational contributions of the material. The tuning is accomplished by controlling the propagation direction. Although the interaction is highly efficient, it should be noted that most of the generated THz waves are absorbed or totally reflected inside the crystal due to a large absorption coefficient, as well as a large refractive index in the THz range (∼5.2). To allow the THz radiation a cut had been made in the corner of the crystal.7–9

It is to our surprise that as far as we know no research has been reported on this novel method since 1976. In this letter, we report an efficient and wide tunable generation of coherent THz wave based on the principle of the previous works, but far better efficiency by introducing the grating coupler on the LiNbO3 crystal surface to couple out the THz wave directly to the free air space.

The experimental setup is depicted in Fig. 1. A 3.5-mm-thick LiNbO3 z plate was cut to a dimension of \( 50(\times) \times 10(\times) \times 3.5(\times) \) (mm³). Two end surfaces of the x plane were cut parallel, polished, and AR coated at 1.07 μm. The relation between the grating period \( \Lambda \) and the \( n \)-th-order radiation angle \( \theta_n \) to the grating surface is given by

\[ \theta_n = \cos^{-1}(n_T \cos \delta - N\lambda_T / \Lambda), \]

where \( \delta \) is the incident angle to the grating, and \( n_T \) is a refractive index of LiNbO3 at THz. The grating couplers were fabricated on the y surface by precise machining using a cutting saw (DISCO DAC-2SP/86), whose pitch, depth, and length were 125 μm, 60 μm, and 10 mm, respectively.

The crystal was placed inside the cavity as shown in the figure, which was resonated at the idler wave using two high-reflection mirrors, \( M_1 \) (\( r = \infty \)) and \( M_2 \) (\( r = 10 \) m). The half-area of both mirrors were coated, and the pump beam was traversed at the uncoated portion.

The pump, the resonated idler, and the generated THz waves were set up to be consistent with the noncollinear phase-matching condition as shown in the inset of Fig. 1. The angle between the pump and idler is on the order of a few degrees. A Q-switched Nd:YAG laser (SOLAR LF113, 1.064 μm) was used as the pump source, whose electric field is along the z axis. Its pulse width, repetition, and typical pulse energy were 25 ns, 16.7 pps, and 30 mJ/pulse, respectively. The idler wave as well as the pump was aligned so as to pass through the crystal as close to the y surface as possible to minimize the absorption effect to the THz radiation. THz output was detected using a silicon bolometer (Infrared Lab.) operating at 4 K. In order to suppress its response at near-infrared and midinfrared regions, a Yoshinaga filter was installed inside. A Schottky barrier diode (SBD) was also utilized to detect the temporal characteristic of THz waves.
whose time response was faster than 10 GHz.¹⁰

Near-infrared idler oscillation around 1.07 μm was clearly recognized by its oscillating spot above the threshold pump power density of 130 MW/cm², whose e field was polarized along the z axis. At the same time, the THz wave was generated inside the crystal at an angle satisfying the momentum conservation relation. The wavelength of the monochromatic THz wave is easily measured by using a scanning etalon made of two GaAs wafers. Figure 2(a) shows an example of the measurement. Figure 2(b) shows the tuning characteristics between the incident angle of the pump to the x surface of the crystal normal and generated THz wavelength measured by the above mentioned method. By changing the incident angle of the pump for 1°, the near-infrared idler wave could be tuned in the range of 1.068–1.072 μm, while the THz wave 290–140 μm. The solid curve indicates the calculated tuning curves based on the dispersion both at near-infrared and THz ranges.¹¹

Figure 3 shows the temporal wave forms of (a) pump (1.064 μm), (b) idler (1.069 μm), and (c) THz wave (150 μm), respectively. Widths of idler and THz waves were almost the same of 10 ns, while that of the pump was 25 ns. The radiation angle of the THz wave to the grating plane ranged between 47° and 88°, while the generated wavelengths ranged from 184 μm to 270 μm, which were in good agreement with the calculation based on Eq. (1). The intensity distribution of the generated beam was Gaussian-like both along and perpendicular to the grating. The measured beam divergences were 1.5° along the x axis and 3° along the z axis which were determined by the length of the grating and the pump beam spot size, respectively. Polarization direction of the THz beam was also assured to be along the z axis using a wire grid polarizer.

The THz output from the grating coupler was estimated to be of the order of mW based on the sensitivity of the bolometer used. We also performed the experiment to couple out the THz wave from the angled surface.² Under the same experimental conditions, the grating coupler produced 250 times or higher efficiency than from the angled surface.

In conclusion, we have demonstrated an efficient coherent THz-wave generation utilizing a grating coupler on LiNbO₃. Tunable nanosecond THz-wave generation with both good temporal and spatial coherence was achieved. Further studies may increase the efficiency, widen the tunability and move toward continuous operation using different materials such as LiTaO₃, KTP, BNN, GaAs, etc. Available coherent THz-wave sources at present are only free-electron lasers and sub-mm-wave gas lasers. Comparing those, the present parametric method has large advantages in compactness, tunability, and ease of handling, so that wide application fields would be expected to open the unexplored THz-wave science and technology. These applications could include spectroscopy, communication, medical and biological applications, THz imaging, etc.

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