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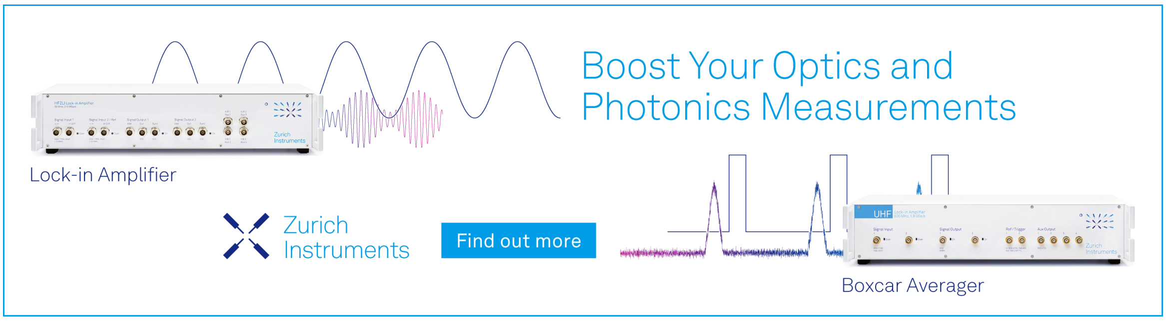

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Terahertz-wave surface-emitted difference frequency generation in slant-stripe-type periodically poled $LiNbO_3$ crystal

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We demonstrate terahertz-wave (THz-wave) surface-emitted difference frequency generation with nanosecond pulse duration. A slant-stripe-type periodically poled lithium niobate (PPLN) crystal was used to realize the quasi-phase-matching in two mutually perpendicular directions of optical and THz-wave propagation. A THz-wave with a wavelength near 200 μm was generated by mixing the radiation of a dual-signal-wave optical parametric oscillator based on a periodically phase-reversed PPLN crystal. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1518779]

The generation of terahertz (THz) radiation is of interest for a variety of applications in basic and applied physics. The difference frequency generation (DFG) is a convenient technique for producing coherent THz radiation,[1] although the efficiency of generation is, as yet, low.[2] One of the limiting factors is the large absorption of THz waves in nonlinear materials. For example, widespread $LiNbO_3$ crystal has a coefficient of absorption of approximately a few tens cm^{-1}.[3] To prevent absorption of the generated wave, two new schemes of DFG have been suggested theoretically. One method[4] is based on coupling the radiated mid-infrared wave out of a nonlinear waveguide into an adjacent linear waveguide before it gets absorbed. However, this is not feasible for THz-wave DFG, because the radiated wavelength exceeds the wavelength of the exciting optical radiation by two orders of magnitude. The other method is surface-emitted THz-wave DFG in a periodically poled lithium niobate (PPLN) waveguide.[5] By choosing the appropriate grating period, the THz wave is radiated perpendicular to the propagation direction of the optical waves. In contrast to collinear geometry, the path length within a nonlinear material is reduced considerably; therefore, dumping of the THz-wave is minimized.

It is interesting to extend this idea to a bulk PPLN crystal. In this case, the THz-wave power can be much higher as a consequence of using powerful optical radiation with a large beam spot, r. However, destructive interference of the radiated THz waves occurs when the beam spot is not much smaller than the radiated wavelength in the crystal, λ_{THz}. A strongly focused beam ($r \approx 10\ \mu$m) has been used to generate surface-emitted THz radiation by optical rectification of a fs-pulse in PPLN crystal.[6] However, beam focusing limits effective interaction length, and does not allow the use of powerful exciting radiation, especially in the case of DFG by nanosecond lasers.

The destructive interference of radiated THz waves can be partially compensated for by sign modulation of the nonlinear coefficient (d_{33}) along the direction of THz-wave emission. A similar method is usually used for surface-emitted second harmonic generation in multilayer AlGaAs[7] and a poled-polymer waveguide.[8] In the case of surface-emitted THz-wave DFG, sign modulation of the coefficient d_{33} is also necessary along the direction of propagation of the optical waves. A $LiNbO_3$ crystal with slant-stripe-type periodic domain inversion[9] can be used to realize quasi-phase-matching (QPM) interaction in the two mutually perpendicular directions of optical and THz-wave propagation.

In this letter, we propose surface-emitted THz-wave DFG in slant-stripe-type PPLN crystal. This is illustrated in

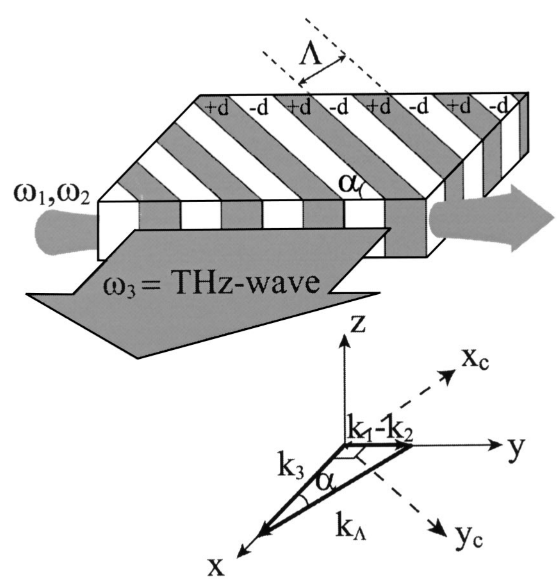

FIG. 1. Schematic illustration of slant-stripe-type PPLN (upper) and the wave-vector diagram (lower), d: nonlinear optical coefficient.

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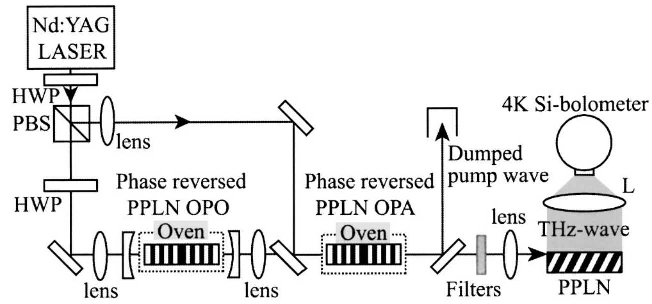

FIG. 2. Experimental setup for THz-wave surface-emitted difference frequency generation. HWP: half-wave plate, PBS: polarizing beam splitter, L: polyethylene lens.

Fig. 1, where x_c, y_c, and z are crystallographic axes of the crystal; the x and y axes are oriented in the directions of optical and THz-wave propagation, respectively. Optical waves with frequencies ω_1 and ω_2 are propagated as close to the lateral face of the crystal as possible and are polarized along the optical z-axis of the crystal. The THz wave (at frequency $\omega_3 = \omega_1 - \omega_2$) is emitted perpendicular to the surface of the crystal. Damping of the THz wave is small, due to the short path length in the nonlinear crystal. The necessary grating period Λ, and angle α, between the direction of optical beam propagation and the domain wall of the PPLN structure can be calculated by using the vector phase-matching condition:

$$K_\Lambda \sin\alpha = k_1 - k_2, \tag{1}$$

$$K_\Lambda \cos\alpha = k_3, \tag{2}$$

where $K_\Lambda = 2\pi/\Lambda$ is the grating wave number, $k_j = \omega_j n_j / c$, $j = 1,2,3$, and c is velocity of light.

Equation (1) means that the phase of the driving source (nonlinear polarization) is not changed along the direction of optical beam propagation. Therefore, each thin sheet of induced dipoles parallel to (xz)-plane radiates THz waves mainly normal to the sheet. Equation (2) incorporates the constructive interference of THz waves. According to Eq. (2), the adjacent domains of the PPLN structure (with a different sign of the nonlinear coefficient) are spaced $\lambda_{\mathrm{THz}}/2$ apart in the direction of THz-wave emission. The solutions of combined equations are

$$\alpha = \tan^{-1}\left(\frac{k_1 - k_2}{k_3}\right), \tag{3}$$

$$\Lambda = \frac{2\pi}{k_1 - k_2} \sin\left[\tan^{-1}\left(\frac{k_1 - k_2}{k_3}\right)\right]. \tag{4}$$

Using these equations, the required angle α, grating period Λ, and THz wavelength are easily estimated. For example, we have $\alpha \approx 22.9°$ and $\Lambda \approx 35.4\ \mu$m if a THz wave with $\lambda = 200\ \mu$m is radiated by mixing the optical waves of 1.5-μm-wavelength region.

The experimental setup is shown in Fig. 2. A Q-switched Nd:YAG laser (wavelength 1.064 μm; pulse width 25 ns; repetition rate 50 Hz) was used as the pump source for optical parametric oscillation (OPO) and optical parametric amplification (OPA).[10] The periodically phase-reversed PPLN (ppr-PPLN)[11] crystal has a phase reversed period in addition to a conventional QPM grating period. In this structure,[12]

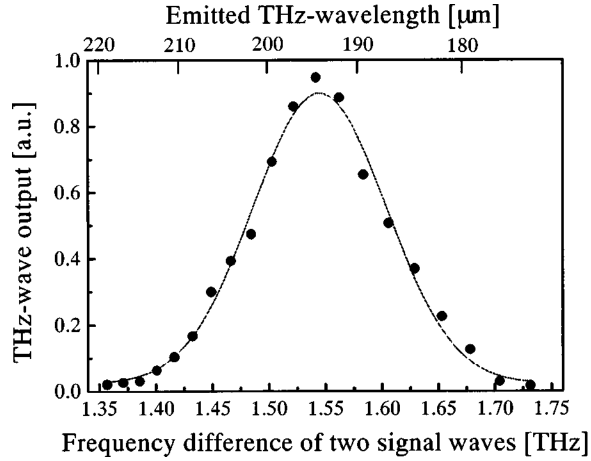

FIG. 3. The tunability of surface-emitted DFG without crystal rotation.

two kinds of phase-matching conditions can be satisfied, so that two pairs of signal and idler waves can be generated from a pump-source. The ppr-PPLN crystal for the master OPO was 0.5 mm thick and the interaction length was 34.8 mm. The QPM grating period and phase-reversed period were 29 μm and 11.6 mm, respectively. The phase-reversed period and QPM grating period of the ppr-PPLN used for power OPA were the same as those of the crystal used for OPO, but the crystal was 1 mm thick, enabling higher pumping. The pump beam was reflected to dump by dichroic mirror and the two idler waves were absorbed into the mirror substrate. Two closely spaced signal waves were used for difference frequency mixing. The waves generated from the ppr-PPLN had good spatial and temporal overlap because of the gain characteristic. The interval between the two signal wavelengths can be tuned from 9 to 14 nm by varying the crystal temperature. This interval resulted in THz wavelength tuning 168 to 240 μm.

The slant-stripe-type PPLN used for DFG was 0.5 mm thick, with a 32 mm interaction length, $\Lambda = 35\ \mu$m, and $\alpha = 23°$. Both the facets of the PPLN were anti-reflection coated for the two signal wavelengths. The two signal beams were focused to about 200 μm at the midpoint of the PPLN crystal in the optical propagation direction. The output of the THz wave generated from the PPLN was measured using a Si bolometer. The maximum output of the THz wave was 0.32 pJ/pulse (peak 12.8 μW) with an incident sum signal energy of 0.82 mJ/pulse. This output resulted in lower conversion efficiency compared with other nonlinear method. The main purpose of this report, however, is actual proof of operation principle. The higher conversion efficiency will be achieved by linewidth narrowing of two signal waves, higher input energy, and so on. Figure 3 shows the output characteristics of the THz wave at each wavelength for a fixed input power of two signal waves. The maximum output was achieved at around 195 μm, which was close to theoretical predictions of 200 μm. Figure 4 shows an example of THz wavelength measurement with a scanning Fabry–Perot etalon consisting of two metal-mesh plates. The span between neighboring transmission peaks corresponds to half the wavelength. The measured wavelength of 202 μm was in good agreement with the wavelength expected from the interval of the two signal wavelengths (1.5152 and 1.5265 μm).

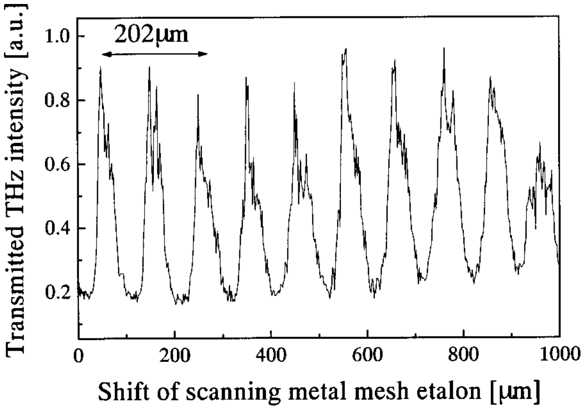

FIG. 4. An example of THz wavelength measurement with a scanning metal-mesh etalon.

In conclusion, surface-emitted THz-wave DFG with slant-stripe-type PPLN is reported. At first, the slant-stripe structure of PPLN, which has a QPM structure for both an optical wave and a THz wave, was proposed and designed. Based on this proposal, we demonstrated THz-wave DFG by combining slant-striped-type PPLN and two signal waves with ppr-PPLN. In the case of surface-emitted DFG, since absorption of the THz wave within a crystal can be reduced and THz wavelength generated can be decided by the grating period (Λ) and angle (α), it may be possible to achieve wider THz region than the that of TPG using lithium niobate crystal (0.7 THz–2.4 THz).[13]

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