Chapter

Optical Heterodyne Measurement of Terahertz Wave

Shin'ichiro Hayashi and Norihiko Sekine

Abstract

One of the most notable frequency regions in terms of research currently lies in the 'frequency gap' region between microwaves and infrared: terahertz wave. Although new methods for generating and detecting terahertz wave have been developed, few detectors operating at room temperature are able to capture low-energy terahertz beams. Here we introduce the optical heterodyne measurement (nonlinear frequency up-conversion detection) of terahertz wave using parametric wavelength conversion in a nonlinear crystal; this has better sensitivity than many commonly used thermal detectors such as pyroelectric detectors. Additionally, optical heterodyne techniques allow the beams of terahertz wave to be visualized and their frequency and intensity determined directly as visible light. These are very promising for extending applied researches into the terahertz region, and we expect that these will open new research fields such as wireless information communications or non-destructive inspection in the terahertz region.

Keywords: terahertz wave, nonlinear optics, parametric wavelength conversion

1. Introduction

Terahertz ($10^{\wedge 12}$ Hz) wave region are important not only in the basic sciences, such as molecular optics, molecular spectroscopy, electron acceleration, plasma measurement, and radio astronomy, but also in numerous applications, such as broadband wireless information communication, non-destructive inspection, high precision radar, and global environmental measurement, since they have higher directivity in the atmosphere than microwaves and higher transmittances in soft materials than infrared. Therefore, sensitive, wideband, coherent detectors for terahertz wave that could be widely used in such applications are required. The terahertz wave region is relatively unexplored because of the lack of the commercially available sources, detectors, and optics which have resulted in what is known as the frequency gap [1–3]. Over the past two decades, there has been remarkable growth in the fields of science and engineering using terahertz wave region, which has become a vibrant, international, cross-disciplinary research activity [4]. An effective method for generating and detecting coherent terahertz waves is wavelength conversion in nonlinear optical materials owing to the high conversion efficiency, wide bandwidth, and room-temperature operation. The large figure of merit (FOM) of $LiNbO_3$ at room temperature makes this well-known nonlinear crystal ideal for such applications; terahertz wave parametric generation and detection in $LiNbO_3$ are realized by stimulated polariton scattering via transverse optical phonons [5–10]. In this paper, we introduce the measurement method of terahertz wave by up-conversion. Terahertz wave is generally measured using thermal detectors, such as Si-bolometers, pyroelectric detectors or Golay cells. Although these detectors can measure the average power, the frequency and the phase information are lost. Furthermore, high sensitivity bolometers require ultralow temperature and show slow response. Thus, there is a critical need for frequency and phase measurements, sensitive and fast detectors that work at room temperature, so that terahertz-wave can be used more widely in a variety of important applications.

2. Terahertz wave parametric wavelength conversion

When a strong electric field, such as that of a Q-switched laser pulse, is incident upon a nonlinear optical crystal, the transverse photon and phonon wave fields become coupled and behave as new mixed photon–phonon states, called polaritons. Broadband terahertz wave generation results from efficient parametric wavelength conversion of laser beam via polaritons [5, 6]. The polaritons exhibit phonon-like behavior in the resonant frequency region (near the transverse optical (TO)-phonon frequency ω_{TO}), however, they behave like photons in the non-resonant low-frequency region, as shown in **Figure 1**. Detecting terahertz wave can be achieved by injecting a "seed" for the broadband terahertz wave. Spectroscopic measurement is accomplished simply by observing the propagation direction of idler beams depending on the angle between the incident pumping beam and the wavelength of the seeding terahertz wave. In the parametric wavelength conversion process, a photon of terahertz wave and a photon of near-infrared idler beam are created parametrically from a photon of near-infrared pumping beam, according to the energy conservation law $\omega_p = \omega_T + \omega_i$ (where ω indicates frequency, and p, T, and i denote the pumping beam, terahertz wave, and idler beam, respectively) and the momentum conservation law $\boldsymbol{k_p} = \boldsymbol{k_i} + \boldsymbol{k_T}$ (noncollinear phase-matching condition). This condition leads to the angle-dispersive characteristics of the idler beams and the terahertz waves. Thus, broadband terahertz waves can be detected depending on the phase-matching angle, as shown in **Figure 2**.

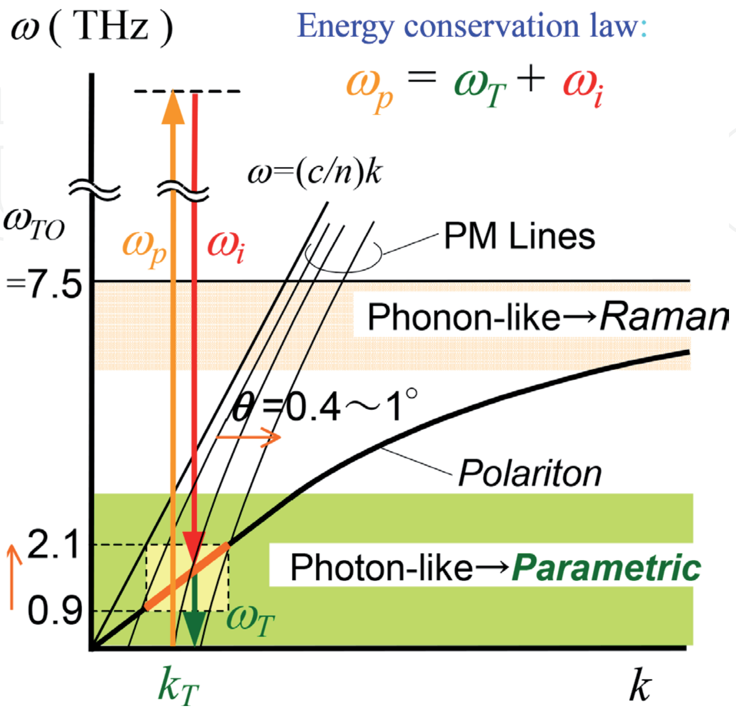

Figure 1.
Dispersion relation of the polariton.

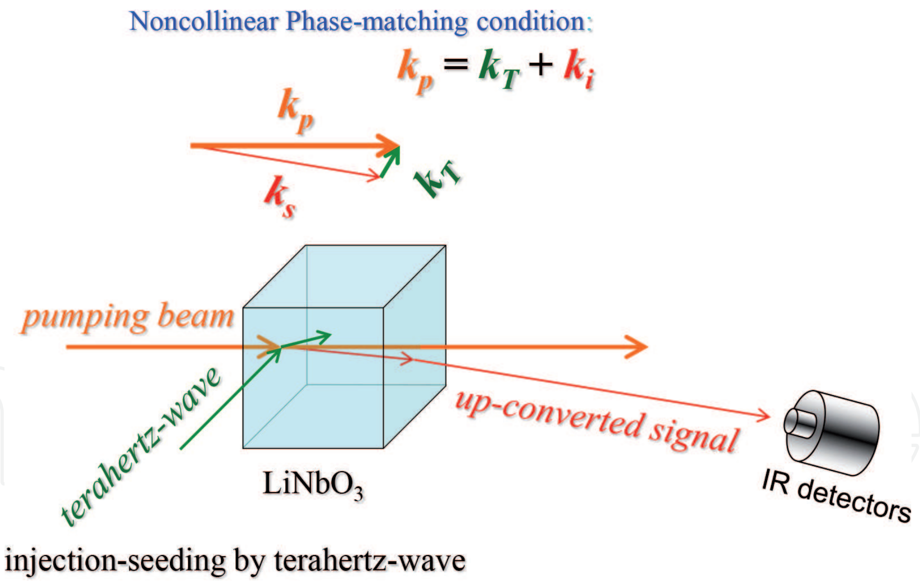

Figure 2.
Noncollinear phase-matching condition.

In our experiment, we used $LiNbO_3$ as nonlinear crystals. The bandwidth of the terahertz wave parametric wavelength conversion is decided by the parametric gain and absorption coefficients in the terahertz region. **Figure 3** shows the calculated gain and the absorption coefficient at the pumping intensity of 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 GW/cm^2 [11]. As the intensity of pumping beam increases, the gain coefficient also increases in whole frequency region, and peak of the gain curve moves towards higher frequencies. All gain curves have a broad bandwidth with a dip appearing at around 2.6 THz because the low frequency modes of doped MgO in the $LiNbO_3$ work as a crystal lattice defects. The effective parametric gain curve depends on the pumping beam intensity and diameter in noncollinear phase-matching conditions. The idler and terahertz wave are parametrically amplified while propagating coaxially with respect to the pumping wave.

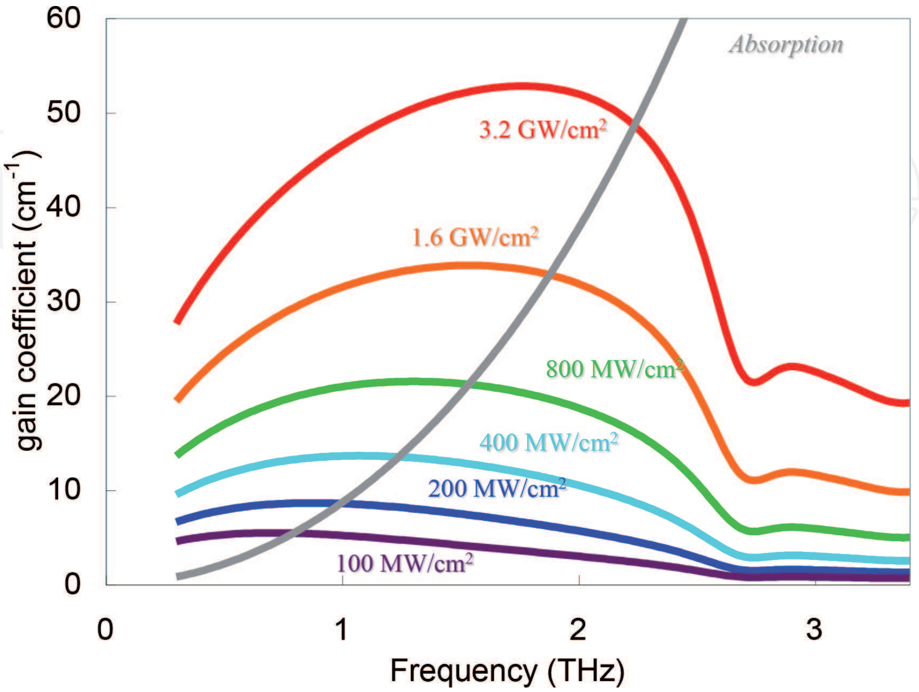

Figure 3.
Calculated gain and absorption coefficient using MgO:$LiNbO_3$ pumped by Nd:YAG laser for several pumping intensities, 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 GW/cm^2.

3. Experiment

The experimental apparatus for terahertz wave spectroscopic measurement shown in **Figure 4** consists of a nonlinear crystal ($MgO:LiNbO_3$) with a Silicon prism and a laser beam visualizer. The terahertz wave was focused onto the $MgO:LiNbO_3$ crystal via Silicon prism input coupler. The incident angle between the terahertz wave and the pumping beam from Nd:YAG based MOPA system satisfies the noncollinear phase-matching conditions in the $MgO:LiNbO_3$ crystal. Mixing the pumping beam with the incident terahertz wave created a seeded, up-converted (difference-frequency) signal, which was parametrically amplified by the optical parametric amplifier in the $MgO:LiNbO_3$. The up-converted signals were visualized using an infrared laser visualizer (10VIZ-35, Standa Corp.) as visible lights; the frequency and intensity was determined from the position and the intensity.

Figure 5 shows pictures of the up-converted signals on the laser beam visualizer when the input frequency of terahertz wave of 1.0, 1.3, 1.6, 1.9 and 2.2 THz. The scales at the bottom show the calculated distance from the pumping beam. The position and the intensity of the up-converted signal depend on the frequency and the energy of the input terahertz wave respectively. As the frequency of the input terahertz wave increases, the position depending on noncollinear phase-matching angle between the pumping beam and up-converted beam also increases,

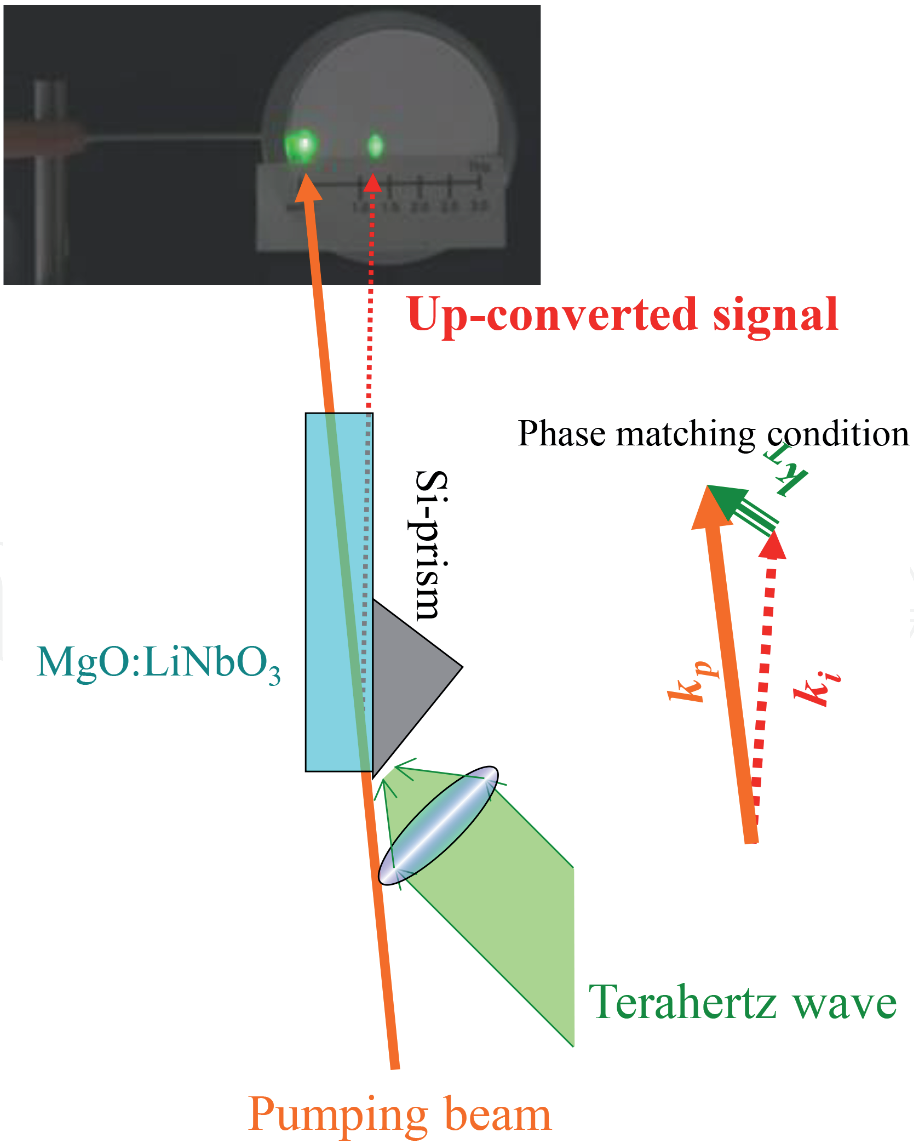

Figure 4.
Experimental apparatus for terahertz wave spectroscopic measurement.

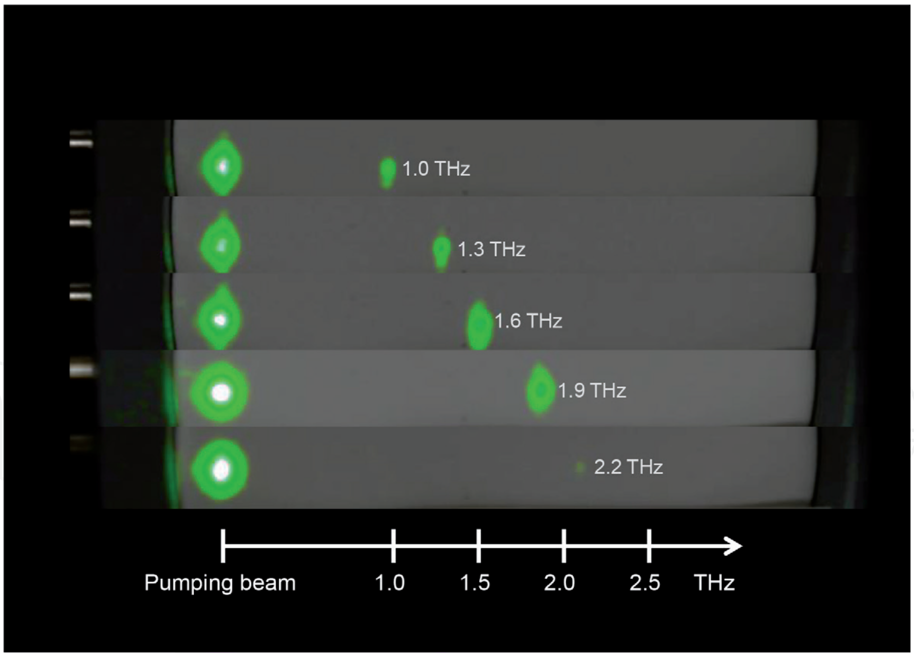

Figure 5.
Pictures of the up-converted signals on the laser beam visualizer when the input frequency of terahertz wave of 1.0, 1.3, 1.6, 1.9 and 2.2 THz.

which shifts the position of up-converted beam. The energy of up-converted beam also depends on the intensity of input terahertz wave, which changes the intensity of the light spot. These make it easy to identify the frequency and intensity of the input terahertz wave from the position and intensity of the up-converted signal. This is in good agreement with the calculation.

Figure 6 shows the input (terahertz wave) – output (up-converted beam) characteristics of optical heterodyne at 1.8 THz when the pumping energy was 10 mJ/pulse. Horizontal axis is input energy of terahertz waves, vertical axis is output energy of the up-converted signals. These colors in the figure represent operating ranges of thermal detectors. The green represents pyroelectric detector at room temperature. The orange represents standard 4 K Si-bolometer. As the input energy of terahertz wave was decreased, the output energy of up-converted signal was also

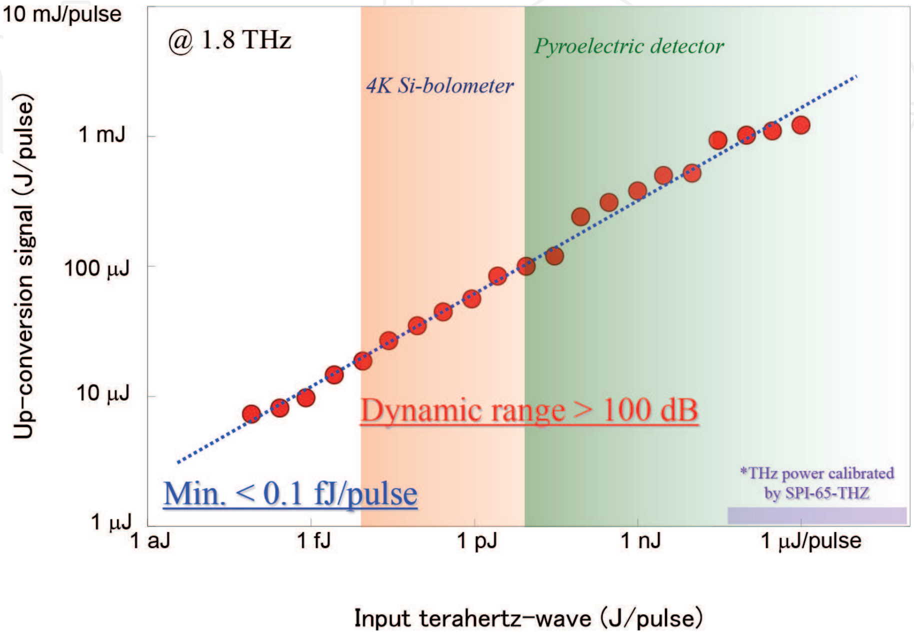

Figure 6.
Output energy of up-converted signals as a function of the input energy of the terahertz wave.

decreased. The maximum energy of up-converted signal was >1 mJ/pulse when the input energy of terahertz-wave was ~1 μJ/pulse. This is easily visualized by laser beam visualizer. The minimum detectable energy of terahertz-wave was less than 100 aJ/pulse. This has higher sensitivity than standard 4 K Si-bolometer. Further, dynamic range reached more than 100 dB.

Figure 7 shows our experimental setup for phase measurement. We used an injection seeded parametric generator (is-TPG) as a terahertz wave source. The terahertz wave from an is-TPG was collimated, passed through a delay line (a rooftop mirror on a mechanical stage). The terahertz wave separated by a wire grid polarizer focused to the MgO:LiNbO$_3$ crystal for up-conversion detection. The incident angle between the pumping beam, the seeded idler beam, and the input terahertz wave satisfy the noncollinear phase-matching conditions in the MgO:LiNbO$_3$ crystal. Mixing the intense pumping beam and the seeded idler beam with the terahertz wave created an up-converted signal. In this case, the intensity of up-converted signal depends on the phase difference between the seeded idler beam and the terahertz wave.

Figure 8 shows the energy of up-converted signals as a function of path length difference between the terahertz wave and the seeded idler wave when the input energy of the pumping beam, the terahertz wave and the idler beam were 10 mJ/pulse, 1 μJ/pulse and 1 μJ/pulse, respectively. As the optical pass length difference increases, we observed blinking of up-converted signals due to the interference between the seeded idler beam and the terahertz wave. The intervals of fringe represent the wavelength of input terahertz-wave. The observed intervals of fringe corresponding to the wavelength of terahertz wave are 200 μm. These show excellent agreement with the wavelength of input terahertz wave from the is-TPG.

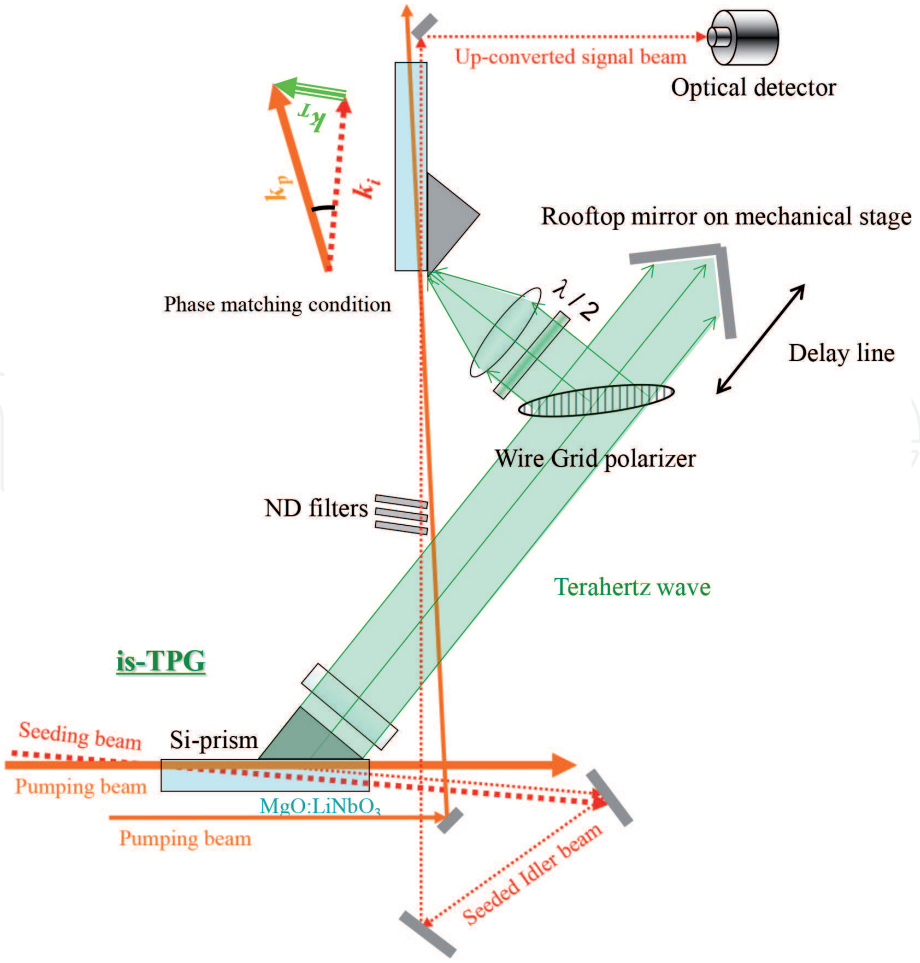

Figure 7.
Experimental apparatus for terahertz wave phase measurement.

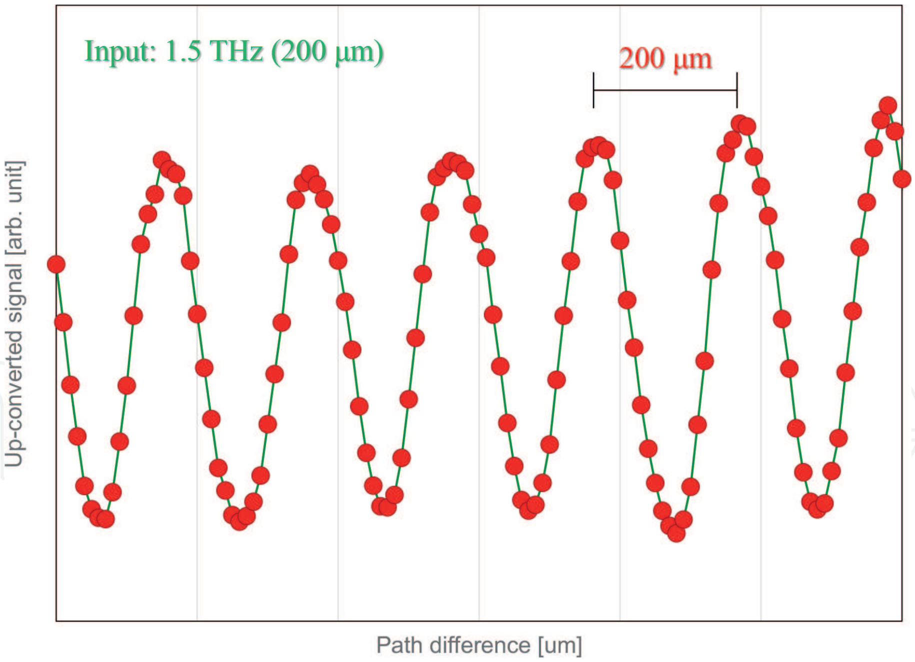

Figure 8.
Phase measurement of terahertz wave by up-conversion.

4. Conclusion

We have introduced here spectroscopic, sensitive, coherent, wideband terahertz wave optical heterodyne detection via wavelength conversion in MgO:$LiNbO_3$. The coherent detection is very important for the calibration of terahertz wave frequency. In general, the radiation frequency calibration is based on absorption lines of molecular gases as a traceable standard, but there is no radiation frequency standard in the terahertz region [12]. In the case, the spectroscopic information of terahertz wave is measured by well-developed optical measurement methods as a traceable standard. Under the experimental conditions, the observed minimum energy of terahertz wave is less than 100 aJ/pulse. This is much higher sensitivity than many cryogenic thermal detectors. Furthermore, the sensitivity depending on parametric gain of the terahertz wave in $LiNbO_3$ could be higher by cooling the crystal [13]. The conversion efficiency improves by a factor of at least ten at liquid nitrogen temperatures. The sensitive detection of terahertz wave is also essential for many applications. A number of applications require sensitive, spectroscopic and wideband terahertz wave detector such as wireless communication and non-destructive inspection. In the future, we will endeavor to produce high sensitivity and wide bands for applied researches. This system could be powerful tools not only for solving fundamental physics but also real world problems such as manipulation or alteration of atoms, molecules, chemical materials, proteins, cells, chemical reactions, and biological processes, and real-time spectroscopic imaging, remote sensing, 3D-fabrication.

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