Generation of Narrowband Tunable THz-Radiation via Optical Rectification in Periodically Poled Materials

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Abstract. The generation of tunable THz-radiation via optical rectification of fs-pulses in periodically poled nonlinear materials is reported and its application for biomedical sensing using THz-sensors based on planar wave guides is discussed in detail.

Key words: optical rectification, poled materials, Terahertz generation

1. Introduction

THz-generation via optical rectification of fs near infrared pulses has proven to be very efficient for the generation of tunable narrowband THz-pulses [1–5]. In particular, the emission of THz-radiation perpendicular to the propagation of the near infrared pump pulse allows for efficient generation as the influence of any strong absorption of THz-radiation in the nonlinear material can be reduced considerably. The generated THz pulses are characterized by an adjustable relative bandwidth and center frequency. The center frequency is determined by the poling period whereas the relative bandwidth scales with the number of poled periods used for THz generation. In this way the characteristics of the generated THz pulses can easily be adjusted to the particular application, e.g. gas sensing, imaging or detection of biomolecules.

2. THz Generation in Periodically Poled Materials

An ultrashort bandwidth limited (pulse length $\Delta\tau$) near infrared pulse with a Gaussian temporal and spatial profile propagates in a periodically poled nonlinear material (Figure 1) along its x-axis and is polarized along the z-axis. The pulse is rectified in each domain of the periodically poled nonlinear crystal. As the nonlinearity of the material changes its sign after each domain an alternating low frequency

Figure 1. Geometry of the periodically poled nonlinear crystal for optical rectification.

polarization is generated. This second order nonlinear polarization P_{nl} acts as a source for a THz wave to be emitted in forward and backward direction as well as perpendicular to the surface. The radiated field can be determined using the radiating antenna model which results in the far field electric field distribution in the frequency domain.

The frequency of the generated THz radiation as a function of observation angle is then given by:

$$\nu_{THz} = \frac{c}{\Lambda} \cdot \frac{1}{n_{IR} - n_{THz} \sin \Theta} \quad (1)$$

where Λ stands for the poling period, Θ for the angle between surface normal and direction of observation ($\Theta = 90^\circ$: forward direction, $\Theta = -90^\circ$: backward direction, $\Theta = 0^\circ$: emission perpendicular to the surface) and n_{IR} and n_{THz} for the index of refraction for the near infrared pump pulse and the THz pulse, respectively.

For THz-emission perpendicular to the direction of the pump beam (surface emitted THz-wave) the absorption of the THz radiation in the nonlinear material which is large e. g. for lithium niobate, can be minimized provided that the near infrared pump pulse propagates as close as possible to the emitting surface. In this case a small spot size of the near infrared beam is required [4] in order to account for the conservation of momentum. The maximum spot size which still allows for emission of THz radiation perpendicular to the direction of pump beam propagation depends on the poling period as well as the refractive indices n_{THz} and n_{IR} at the generated THz- and the near infrared wavelengths, respectively. From our theoretical considerations we obtain

$$w_0^{\max} \leq \frac{\sqrt{2} \cdot \Lambda \cdot n_{IR}}{\pi \cdot n_{THz}}. \quad (2)$$

3. Experimental Results

Our experimental set-up (see Figure 2) consists of a conventional THz-setup (100-fs Ti:sapphire laser operating at 780 nm with a repetition rate of 82 MHz, average output power up to 1.5 W) with periodically poled lithium niobate (PPLN) as the

Figure 3. Comparison between experimentally obtained data (dots) and theoretical simulation (solid lines) for a THz-pulse emitted perpendicular to the direction of beam propagation in PPLN: a) temporal profile and b) spectral profile. The dip in the spectral profile is caused by a water vapor absorption line.

Figure 4. Schematic drawing of the THz wave guide sensor.

4. THz Waveguide Sensors

The PPLN THz source was used to investigate the possibility to realize sensors for biomolecules. The THz sensors investigated here consist of thin dielectric planar wave guides. The THz radiation is coupled into the wave guides via the evanescent field after total internal reflection off a silicon prism as shown schematically in Figure 4. The distance between prism and wave guide determines the coupling strength and is typically in the order of a fraction of the wavelength used (20 μm to 100 μm). The molecules under investigation are deposited on the surface of the wave guide. The dependence of the resonance frequencies of wave guide modes on the deposition is utilized to detect any adsorbates to the surface. The resonance frequency ν_{THz} of TE wave guide modes is given by:

$$\frac{2\pi \cdot \nu_{THz}}{c} \cdot n_{wg} \cdot t \cdot \cos \Theta - \phi_{upper} - \phi_{lower} = m\pi \cdot \nu_{THz} \quad (3)$$

where t , Θ , n_{wg} , ϕ_{upper} and ϕ_{lower} stand for the thickness of the wave guide, the angle of incidence, the index of refraction of the wave guide material and the phase shift during reflection at the upper and lower boundary, respectively. The resonance frequencies can be detected as absorption lines in the spectrum of the reflected THz radiation. A typical result is shown in Figure 5 for the prism without wave guide and with a Silicon wave guide of 375 μm thickness and our THz source tuned to 585 GHz. After division of both spectra the wave guide mode is clearly resolved. The sensitivity to thickness variations was determined by measuring the TE mode for slightly different Silicon wave guide thicknesses ranging from 378 μm to 395 μm resulting in a sensitivity of $-1.36 \text{ GHz}/\mu\text{m}$.

Figure 5. a) Spectral profile without wave guide, b) spectral profile with wave guide and c) divided spectrum showing the wave guide mode.

This shift is only caused by a change of the thickness. No additional changes of the phase shifts during reflection at the wave guide boundaries will occur for pure Silicon. However, additional phase changes (see equation (3)) caused by adsorbates at the surface should give rise to an enhanced frequency shift which then allows for the detection of much thinner layers adsorbed to the surface. In particular, biomolecules with a high polarizability or dipole-dipole interactions will result in a phase shift at the boundary. As the maximum frequency resolution is in the order of 500 MHz for our coherent detection system we expect to be able to detect even thin adsorbates at the wave guide surface. This sensor could then be useful also for label free biomedical sensing applications where a high sensitivity is required.

5. Summary

In summary we have presented a new method to generate THz-radiation via optical rectification in periodically poled materials. Using periodically poled lithium niobate as the nonlinear material THz radiation in the frequency range from 100 GHz to 3 THz has been generated. The bandwidth can be adjusted by changing the number of poled periods involved in the rectification process. This type of radiation was used to investigate wave guide sensors utilizing the evanescent waves at total internal reflection and typical sensitivity limits were determined. It turned out that the effect of thickness changes on the resonant wave guide modes is not sufficient for biomedical sensing. However, additional phase changes at the boundary caused by the adsorbates to be detected may enhance the sensitivity considerably. Thus there is a potential of THz sensors for label free sensing of biomolecules.

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