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Techniques for cancellation of interfering multiple reflections in terahertz time-domain measurements

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Abstract

Algorithms are described which allow a significant reduction of the effects of multiple pulses, which originate from pulse reflections within terahertz (THz) emitters. The algorithms are based on models for the pulse propagation inside the emitter. Model parameters can be estimated from a calibration experiment using a reference signal in the absence of a sample. The parameters once estimated for a particular emitter device, can then be used to suppress the effects of multiple pulses in all measurements performed with the same emitter. The application of this method is demonstrated in the investigation of a disc sample and in the investigation of a paint layer.

Keywords: Terahertz pulses; T-rays; Multiple reflections; Multi-layer systems; Reflection measurements

1. Introduction

Terahertz (THz) radiation or "T-rays" typically describe electromagnetic radiation in the frequency range from 100 GHz to 10 THz. The unique properties of waves in this range make this radiation an interesting candidate for non-destructive investigations. For example many polymer materials, paper and many fabrics are almost transparent in the THz range: THz radiation can therefore be used for packaging inspection and quality control in, for example, the semiconductor industry or the food industry [1]. The non-ionizing energies of THz photons allow safe imaging of skin, and in contrast to conventional microwave measurements the short wavelength results in an acceptable image resolution [2]. The development of coherent detection methods has opened new opportunities for far-infrared spectroscopy with remarkably high signal-to-noise ratios [3]. A longer discussion of the application of THz technology is given in [4,5].

While the development of new THz hardware rapidly progresses, the development of specialized processing methods is still in its early stage. To date, different methods for image reconstruction in THz tomography have been described [6,7], partly adapted from techniques operating at other wavelengths, but often taking into account the special features of pulsed radiation. Iterative image processing methods have been developed which improve the accuracy of optical constant measurements of planar samples [8]. In [9] the application of fractional Fourier transform and spectrogram to THz data has been demonstrated. The applicability of different de-noising techniques to THz measurements has also been investigated [10]. These techniques are essential for improving the speed of data acquisition, especially in THz imaging.

In this article we describe a processing method which strongly reduces the influence of a systematic error which often appears in pulsed THz experiments. In this way signal processing is used to improve the quality of THz measurements and to expand the range of possible applications.

A common technique used to produce broad-band THz radiation for use in time-domain spectroscopy and THz-imaging experiments is the laser excitation of

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photoconducting semiconductor emitters [11]. In response to a single laser pulse excitation these devices generate not one, but a sequence of THz pulses with decreasing amplitudes. These additional THz pulses—referred to as multiple reflections from this point onwards—are due to reflections at the interfaces between the semiconductor crystal and its surroundings. As the THz pulse passes through the sample it is modified giving a sample response signal—the multiple reflections give rise to additional sample response signals, which can overlap with the time-domain response to the main THz pulse. Analysis of the resulting time-domain THz signal is then significantly complicated by the presence of the echo signals and in the worse case they can make interpretation of the signal impossible. Separation and suppression of these unwanted multiple signals therefore can significantly improve the quality of THz measurements.

One approach, which is used to suppress such multiple reflections, is to increase the temporal separation of the single THz pulses by manufacturing emitters on very thick substrates, with subsequent truncation of the time-domain response before the start of the first additional reflection. However, truncation limits the spectral resolution Δf in Fourier transform spectroscopy, since Δf is inversely proportional to the duration of the time-domain signal Δt. Subsequent reflected signals are separated by $\Delta t = 2dn/c$, where d and n are, respectively, the thickness and refractive index of the substrate crystal and c is the speed of light. Using an emitter on a 1 mm thick GaAs substrate ($n = 3.6$), a spectral resolution of the order of 40 GHz can be achieved. While this is sufficient for many solid- and liquid-phase samples, the investigation of vapors and gases requires significantly higher resolution [12]. Suppression of the first multiple reflection, for example, would double the maximum spectral resolution. Interfering multiple pulse signals have been reported in gas phase measurements by several authors [13,14].

There are a number of experimental protocols in which the use of thick crystals is not possible (or highly undesirable). One example is THz imaging. In this kind of experiments high-power laser pulses are applied. In order to prevent thermal damage, the emitter crystal is usually mounted onto a metallic heatsink: a thick substrate would be unfavorable in these cases because of the low thermal conductivity of GaAs. On the other hand, the metallic heatsink causes additional reflections of high amplitude, giving rise to strong multiple signals.

Depending on the dimensions of the sample, multiple emitter pulses can also cause significant problems for THz tomography [15].

An application of pulsed THz radiation is the investigation of dielectric multiple layers: information on the layer structure is obtained since there is reflection of the THz pulses at the interface between each. The differences in arrival time of the reflected pulses provide information about the layer thickness—one potential application of such a technique is the non-destructive investigation of paint layers on old-master paintings. Of course signals arising from multiple reflections are also reflected at the layer interfaces and may well overlap with the response to the main pulse, causing significant difficulty in interpreting the resulting data. In [16] a time-domain method for the investigation of thin layers is described, however, the range of time delays in thicker layer structures can be so large, that an overlap of the sample response to the first THz pulse and to signals, that are reflected within the emitter is unavoidable, regardless of whether the emitter is fabricated on a thick substrate crystal.

In this work system theory is used to model the pulse propagation within the emitter. These models allow the derivation of data processing procedures for the separation of the response to the first pulse from the response to multiple reflected signals. Model parameters need to be fitted only once and can then be used for different data sets. In addition to the practical benefit of suppressing unwanted signals, a comparison between measurements and the idealized model behavior provides clear evidence for changes in the optical properties of the emitter material shortly after the application of intense laser pulses. The influence of the laser induced charge carrier plasma on both the index of refraction and absorption coefficient of the semiconductor can be monitored. Experimental results show that pulses propagating through the emitter within the lifetime of this plasma are more strongly absorbed than pulses propagating in the absence of these carriers. These results give complimentary information on carrier dynamics, which is otherwise investigated using time-resolved optical transmission measurements [17], luminescence [18] or time-resolved THz spectroscopy [19].

An alternative approach to solve the multiple pulse problem by signal processing is the application of a deconvolution algorithm to the time-domain data set. In this case the time-domain response is replaced with broadened delta pulses, where the broadening depends on the bandwidth of the THz system [20]. This can be a valuable tool for the investigation of multiple-reflector systems, since amplitude and sign of the single delta pulses are proportional to the amount and phase of the reflected signal. While the actual time-domain waveform is lost by application of deconvolution algorithms, the method described here conserves the time-domain signal shape. The limitation on a small number of fitting parameters results in robust algorithms and avoids the noise-sensitivity of deconvolution methods mentioned in [10].

For measurements where the unwanted reflections appear within the sample, a method is described in [21]. It estimates the sample material parameters and it takes into account the optical properties of the media in front of the sample and behind the sample. The removal of disturbing multiple reflections by fitting polynomials to the logarithm and the argument of the samples transfer function is described in [22].

The appearance of additional reflected signals is a common problem in ultrasound measurements and in