Application of metasurface-based low-pass filters for improving THz-TDS characteristics

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Abstract. We propose an approach to improve the technical characteristics of terahertz time-domain spectrometers at low-frequency measurements. The approach is based on applying low-pass THz filters to narrow the frequency band of the THz signal that allows increasing the sampling interval in accordance with the Nyquist–Shannon theorem. This concept was verified by studying the transmission spectra of low-frequency band-pass THz filters centered at 156 and 376 GHz. We confirm that the high-quality low-pass filters can improve accuracy of THz measurements and significantly reduce data acquisition time. The reduction up to 12 times was experimentally demonstrated in our case.

1. Introduction

Due to a progress in femtosecond laser technologies, terahertz (THz) time-domain spectroscopy (THz-TDS) has become a most frequently used method for studying dielectric properties of matter. THz-TDS utilizes a principle of probing a medium with a short electromagnetic pulse, which is a single-period oscillation of ~1 ps duration carrying a wide band of frequencies. The advantage of the method is a direct measurement of the electric field waveform that provides information about amplitude and phase of the THz radiation. The detection is based on discretization and analog-to-digital conversion (sampling) of the waveform. Further processing takes place in a digital domain, including Fourier transform of the time-domain signal. Thus, the Nyquist–Shannon sampling theorem is valid for THz-TDS, imposing a restriction on the maximum sampling interval defined by the device’s optical delay line step Δt.

It is worth noting that modern commercially available THz spectrometers are capable of covering a wide spectral band ranging from 50 GHz to 6 THz [1,2]. Meanwhile, there is a number of applications wherein only the low-frequency sub-range of the THz spectrum is relevant. These applications include, for example, studies of soft modes in ferroelectrics, which frequencies tend to zero at the phase transition temperature [3]; developing instrumentation for the future telecommunications range: 100–300 GHz [4–6]; studying solutions of highly absorbing liquids [7]; designing and testing metastructures, including sensors with characteristic resonances located in a limited low-frequency band of the THz spectrum [8,9], and many others. In all these tasks, the higher frequency part of the THz signal often contains no useful information, however, it requires a value of Δt small enough to satisfy the Nyquist theorem and to detect the THz signal without aliasing distortion.

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In this work we propose an approach that amends technical characteristics of THz-TDS at low-frequency measurements. It exploits an idea of applying high-performance low-pass filters (LPFs) to narrow the band of the THz signal that allows us to increase the sampling interval $\Delta t$. As a result, due to increased averaging time at each sampling point, significant reduction of the data acquisition time or augmentation of the signal-to-noise ratio (SNR) are feasible. The idea of applying LPFs is not fundamentally novel and was considered in Fourier transform far infrared spectroscopy to prevent the IR detector from saturating with high-intensity IR radiation. However, in THz-TDS this approach was not previously examined. We tested it by the example of our TDS system (full bandwidth up to 2.7 THz) using four different LPFs. Two band-pass filters (BPFs) centered at 156 and 376 GHz served as the references which transmission spectra were thoroughly measured. The results were compared with the data obtained by backward wave oscillator (BWO) based spectroscopy.

2. Methodology

All the filters used in this work were implemented as multi-layer plasmonic structures based on metasurfaces produced photolithographically [10–12].

BPFs with the center frequencies of 156 and 376 GHz and bandwidth of about 12% were assembled from three (156 GHz) and four (376 GHz) free-standing substrate-free patterned copper foils [12]. These multilayer structures had a multiplex (non-interference) configuration providing the out-of-band transmission at the level of −40–50 dB up to IR frequencies with no spurious transmission peaks.

The LPFs were represented by interference structures with 6 layers of capacitive patch-like metasurfaces patterned on polypropylene substrates and stacked together by means of a hot-pressing technique. The LPFs provided −30–40 dB of THz attenuation above their cutoff frequencies positioned between 0.2 and 2 THz (fig 1). A detailed description of LPFs will be published elsewhere.

Testing was carried out at room temperature using a manufactured in-house THz-TDS system: spectral range 0.1–2.7 THz, dynamic range more than 60 dB @ 0.3 THz. A detailed description of the installation can be found in [6]. The measurements were performed in a collimated beam shaped by a 16 mm round diaphragm which diameter was limited by the aperture of the manufactured LPFs. The clear aperture diameter of the BPFs was 75 mm. The sampling range of the spectrometer was 120 ps, which corresponds to a spectral resolution of about 10 GHz. An averaging time at each point is 0.7 s with 100 ms lock-in amplifier time constant. So, a typical single scan took about 11 minutes 12 s.

LPFs characteristics were previously investigated on the same THz-TDS system (fig. 1). Table 1 presents estimated values of the cutoff frequencies for the signal level of 0.5 ($f_{0.5}$) and 0.01 ($f_{0.01}$). In accordance with the Nyquist–Shannon theorem the sampling step $\Delta t$ was selected for each filter. The Nyquist frequency ($f_{ns}$) for the corresponding sampling step and acquisition time reduction ratio are listed in the last columns of table 1.

| Filter No. | $f_{0.5}$ (GHz) | $f_{0.01}$ (GHz) | $\Delta t$ (fs) | $f_{ns}$ (GHz) | Ratio |
|-----------|----------------|-----------------|----------------|----------------|-------|
| 1         | 208            | 248             | 1500           | 333            | 12    |
| 2         | 434            | 503             | 750            | 666            | 6     |
| 3         | 845            | 1018            | 375            | 1333           | 3     |
| 4         | 1466           | 1682            | 250            | 2000           | 2     |
| No filter | -              | -               | 125            | 4000           | 1     |

3. Results and discussion

The measurement results for BPFs are presented in fig. 2 (156 GHz) and fig. 3 (376 GHz). The obtained discrete spectra are interpolated by a cubic spline in order to accurately determine the BPF peak transmittance, the frequency ($f_{\text{max}}$) of transmission maximum, and the bandwidth (FWHM). The
extracted numbers are shown in Table 2 and 3. Since the pass-band of the 376-GHz-BPF lies above the cutoff frequency of the LPF 1, this data is not presented.

**Figure 1.** LPFs transmission spectra.  
**Figure 2.** Transmission of the 156 GHz BPF.  
**Figure 3.** Transmission of the 376 GHz BPF.

| LPF No. | 156-GHz-BPF | 376-GHz-BPF |
|---------|-------------|-------------|
|         | $f_{max}$ (GHz) | $T$ @ $f_{max}$ (%) | FWHM (GHz) | $f_{max}$ (GHz) | $T$ @ $f_{max}$ (%) | FWHM (GHz) |
| w/o LPF | 155.52 | 95.09 | 18.42 | 11.85 | 376.37 | 89.1 | 43.41 | 11.54 |
| 1       | 156.29 | 93.13 | 18.97 | 12.14 | - | - | - | - |
| 2       | 156.00 | 93.33 | 17.92 | 11.49 | 376.47 | 88.6 | 43.26 | 11.49 |
| 3       | 155.75 | 93.38 | 18.77 | 12.05 | 376.45 | 88.5 | 43.53 | 11.56 |
| 4       | 156.11 | 91.56 | 18.76 | 12.02 | 376.67 | 88.0 | 43.47 | 11.54 |
| Mean    | 155.93 | 93.3 | 18.57 | 11.91 | 376.49 | 88.54 | 43.42 | 11.53 |
| SD      | 0.3 | 1.25 | 0.47 | 0.26 | 0.13 | 0.45 | 0.12 | 0.03 |

In general, the obtained results satisfy our expectations, however some details require explanation. Dispersion of $f_{max}$ is consistent with the absolute resolution value of uncalibrated THz-TDS systems, which is not better than 1 GHz. The accuracy of the transmission maximum is related to the SNR of the THz generator, which is approximately 2.5 times greater for 376 GHz than for 156 GHz.

In both cases measured without LPFs the peak transmittance of the BPF exceeds the other values. This can be attributed to the long-term drift of the THz signal in our system as the data acquisition time without LPFs is longer (2 times relative to the closest measurement with LPF 4) and, therefore, most susceptible to this effect. For the same reason we were not able to show measurement noise reduction due to increased averaging time at each sampling point. Apparently, it is necessary to accurately control the ambient humidity and temperature to track this effect, that wasn’t done in these experiments.

In general, a larger dispersion of the obtained values for the 156 GHz filter is probably related with the spectral dependence of the system dynamic range and SNR. The frequency of 376 GHz is closer to the maximum dynamic range of the spectrometer than 156 GHz, which is located near the low-frequency edge. The noticeable deviation of the measurement with LPF 1 for the 156-GHz-BPF can be explained by more pronounced diffraction effects for longer waves.

**Conclusion**

In this work, we investigated the relevance of using metasurface-based multilayer structures as low-pass (aliasing) filters in THz-TDS when studying the transmission spectra of low-frequency BPFs. As a result of cutting off the high-frequency components of the THz signal and increasing the sampling step in accordance with the Nyquist-Shannon theorem, the scanning time was reduced up to 12 times.
At the same time, the measured values remained within acceptable limits corresponding to the uncalibrated and unstabilized spectrometer. The characteristics of 376-GHz-BPF, which pass-band is located closer to the maximum dynamic range of the spectrometer, have a smaller dispersion than those of 156-GHz-BPF. Measurements carried out without low-pass filters deviate from all the others, that is probably related to the longest measurement time and, therefore, the contribution of the long-term drift of the THz signal. We confirm that a high-quality LPFs can significantly reduce the data acquisition time and improve measurement accuracy, at least by diminishing the long-term effects. In particular, for modern THz-TDS systems with a bandwidth of 5 THz and higher the time reduction factor of 20 can be achieved.

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