Supplementary Material

Standing wave pattern suppression in the terahertz frequency domain spectroscopy by means of windowed Fourier filtering

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A. Fringe structure of the transmittance spectrum

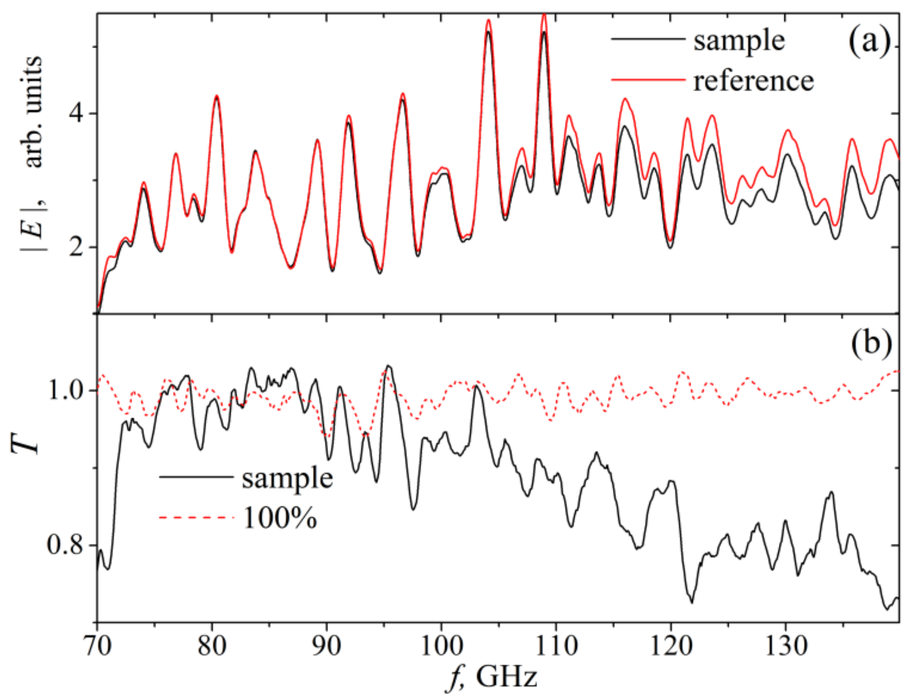

Fig. S1. (a) Frequency dependence of the measured terahertz signal with and without the metamaterial sample after twice repeated adjacent averaging over 1 GHz. (b) Frequency dependence of the transmittance calculated from the signals depicted in (a) and 100% line. The 100% line is the squared ratio of the terahertz signal amplitudes of two consecutive runs.

Figure S1a shows the frequency dependencies of the sample and reference signals measured with the step size 0.1 GHz in the off-resonance spectral region of the metamaterial (see Fig. 4a of the main text). The spectra have peaky structure caused by standing waves in Si lenses of the photomixers. Figure S1b represents the sample transmittance and 100% line. Both spectra are distorted by the standing wave patterns (coherent noise) shown in Fig. S1a.

B. The effect of the terahertz absorber on the peaky structure of the measured terahertz signal

To reduce the standing-wave effect on the measured spectra, foam absorbers are placed in the THz beam path. The measurements with and without the absorbers are carried out in two ranges: the lowest frequency edge of the spectrometer (50 GHz, Fig. S2a) and the range of the largest THz power (250 GHz, Fig. S2b). For comparison, the attenuated spectra are multiplied by 30 and 50 in Fig. 2Sa and 2Sb respectively. Because of the frequency dependence of the absorption efficiency, the spectra with and without absorbers do not coincide completely. At first sight, data seems to be very noisy. However, the peaky structure in the spectra is well reproducible in successive measurements indicating that it comes from the standing waves in the spectrometer. Signal oscillations with a period of ≈0.25 GHz caused by Fabry-Perot resonance between photomixers separated by 0.6 m free space are partly suppressed by the absorber (Fig. S2b). We find that the peaky structure almost unaffected at low frequencies. Furthermore, the signal spikes related with standing waves in optical components of the spectrometer cannot be diminished by the absorbers. Some of the spikes may even increase due to degraded signal-to-noise ratio at the strongly attenuated THz power. This effect is more pronounced in lower frequency range where THz power is typically lower.

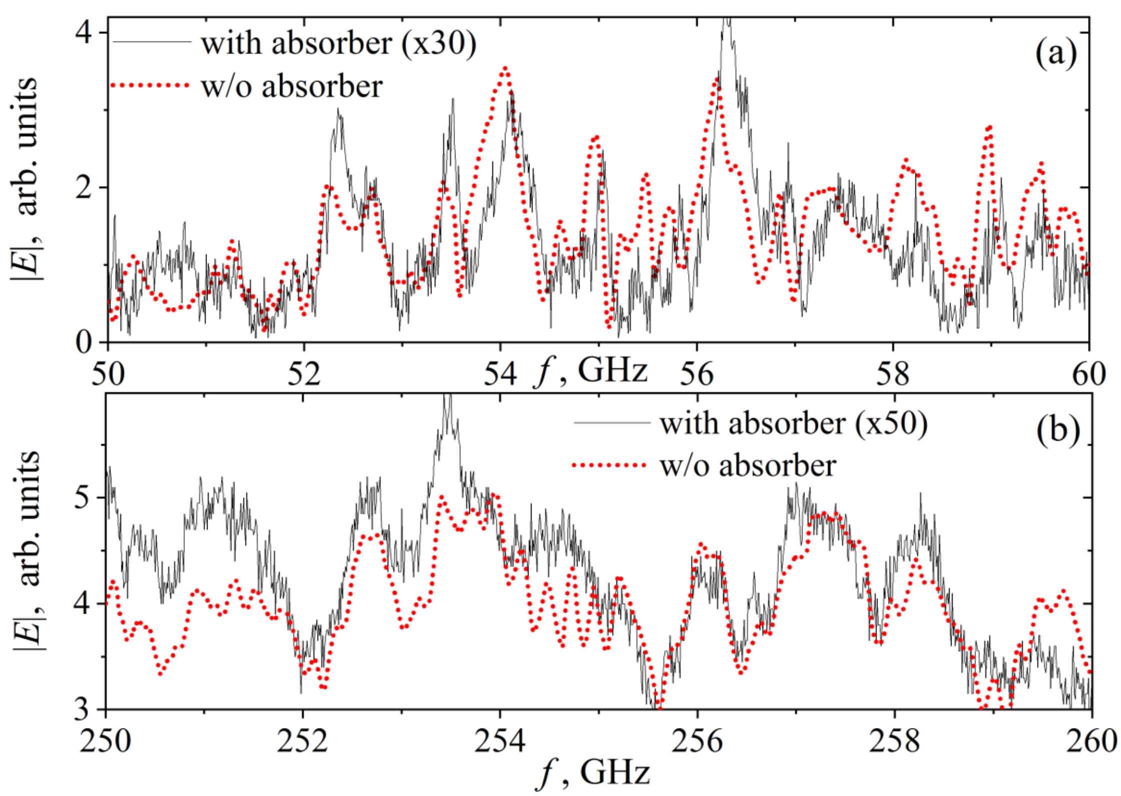

Fig. S2. Comparison of reference spectra measured with and without foam absorbers in the beam path. The signals measured with the absorbers are multiplied by 30 and 50 in (a) and (b), respectively.

C. Instability in the measured terahertz signals

Let us now pay attention to the instability of the signal measured with the terahertz spectrometer TeraScan 780. Figure S3a shows the frequency dependence of the reference signal measured at different moments of time. One can see in Fig. S3a that the spectra have oscillations caused by the Fabry-Perot resonances frequency of which drifts with time by up to 0.5 GHz. As a result, unwanted oscillations appear in the transmittance spectrum. Normally, the frequency shift decreases as the temperature of the spectrometer stabilizes. However, the frequency shift is also affected by other factors, as can be seen from the 100% line measured 270 min after the spectrometer was turned on (Fig. S3). To reduce the influence of the frequency drifting, the time gap between the sample and reference measurements should be decreased.

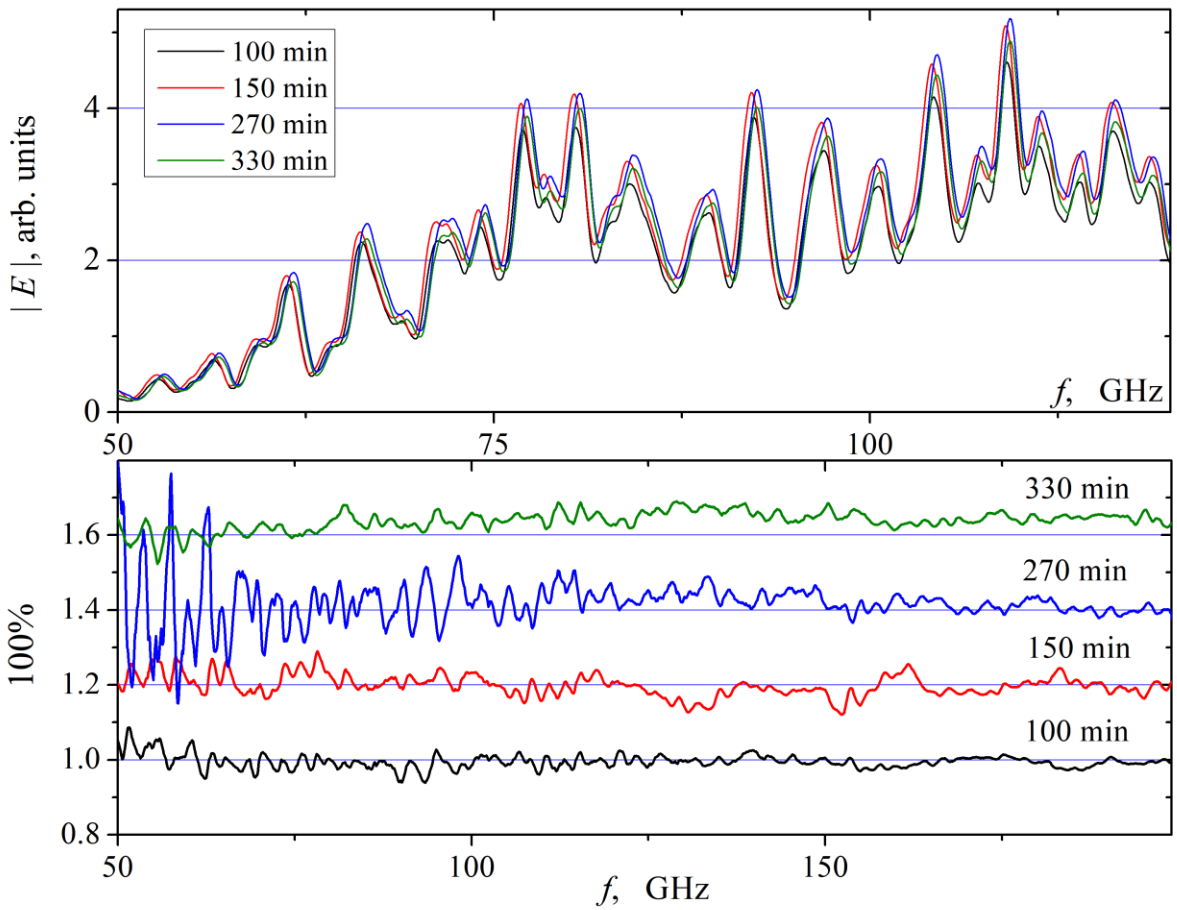

Figure S3. Frequency dependencies of (a) the reference signal and (b) the 100% line measured at different moments of time $t = \{100,150,270,330\}$min after switching the spectrometer on (frequency step size 0.1 GHz). All the spectra are smoothed with adjacent averaging over 1 GHz applied twice. The 100% line is the squared ratio of the signal amplitudes of two consecutive runs.

D. Comparison of the spectra measured with different frequency step sizes.

Figure S4 shows the spectra measured with different frequency step size Δf after windowed Fourier filtering (WFF) with shift compensation. One can see that the overall shape of the spectra at Δf={20, 100} MHz, is similar. However, in the range of the high transmittance (75-110 GHz), the better suppression of the fringe structure is achieved for the measurement with smaller step size as frequency of the fringes is determined with higher accuracy. At Δf = 200 MHz, the WFF method hardly reduces the coherent noise at the chosen width of the time window $2\Delta\tau = 0.88$ ns.

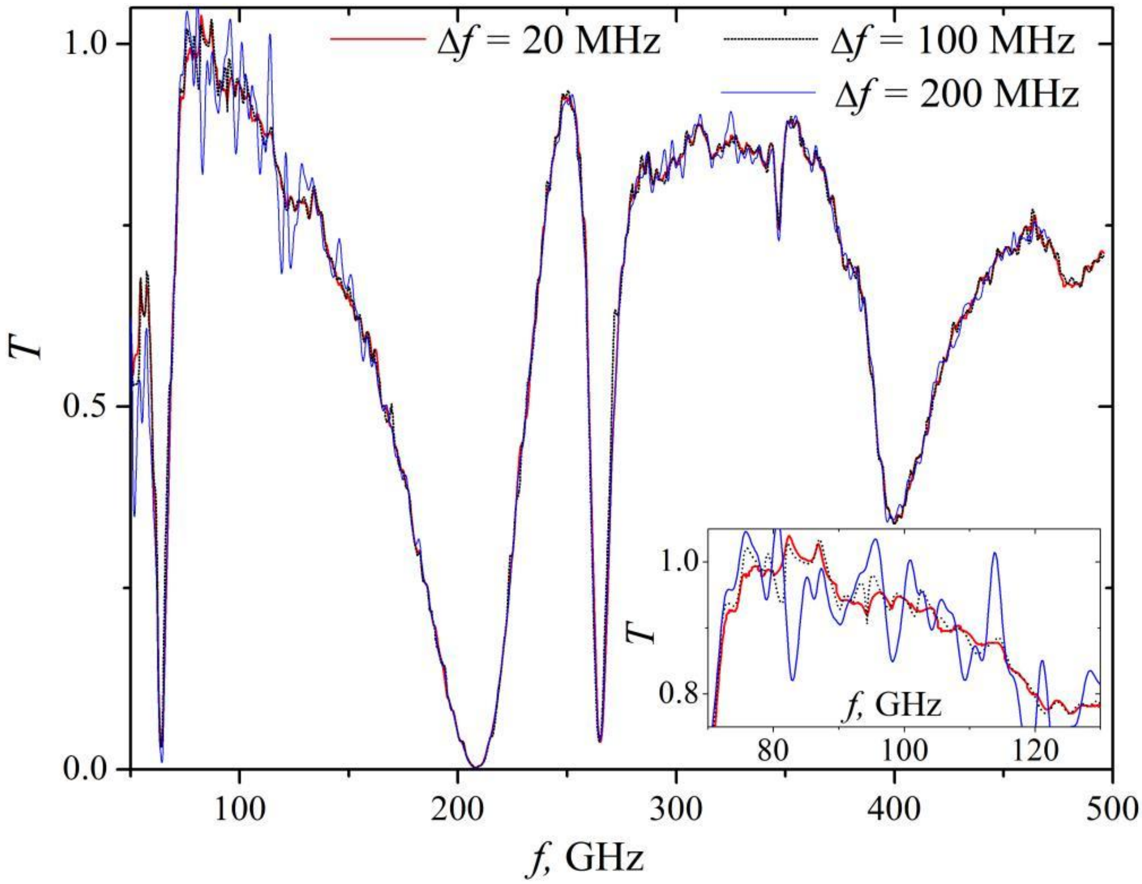

Fig. S4. Transmittance spectra of the metamaterial measured with different step sizes Δf={20, 100, 200} MHz and processed with the WFF with shift compensation. The inset is a close-up view of the large transmission range 70-130 GHz.