Detection of Separation of Laminated Materials by Reflected THz Pulses

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Abstract. A method is described for the detection and measurement of sub-wavelength gaps in laminated non-metallic materials, using numerical processing of returned THz echo pulses. Data from artificially constructed phantoms are presented. Deconvolution using a reference pulse gives depth resolution to a small fraction of a wavelength, enabling corresponding layer separations to be measured.

Introduction

In a typical pulsed THz system, the source is triggered by a fast laser pulse, and the detector is triggered by a delayed part of the same laser pulse. The time delay of detection is controlled by reflecting the second laser pulse at a mirror with precisely controlled movement. It is therefore possible to make accurate measurements of small time delays in the received THz signal. For a mirror movement through distance x, the detector time delay is 2x/c.

For a THz transparent material a few per cent of a THz pulse will be reflected at the surfaces. The pulses reflected from the entry and exist surfaces will have opposite phases. For a laminated structure with an internal air gap, there will thus be four reflected pulses: two positive and two negative. The time separation of the reflections from the faces of the air gap will be proportional to the width of the gap. If the incident signal is inclined at angle θ to the normal to the layers, the time separation of the echoes from a gap with width g is 2g cos θ/c.

The measurement of the size of the air gap is then directly related to the mirror displacement between the two echoes.

$$g = \frac{x}{\cos\theta}.$$

1. Experiment

In order to test this method of examination an experiment is in the process of being set up in which a parallel THz beam is directed at a suitably designed phantom structure, and the reflected radiation is collected and focussed on to a detector. The test phantom consists of two parallel flat sheets of PTFE (transparent to THz) with an adjustable air gap between them. (Figure 1). The phantom is interchangeable with a flat metal reflector to provide a reference pulse, under the same conditions of generation and detection. The reference pulse carries the information needed for signal processing. The remainder of the THz system follows the usual arrangements described in [1-3].

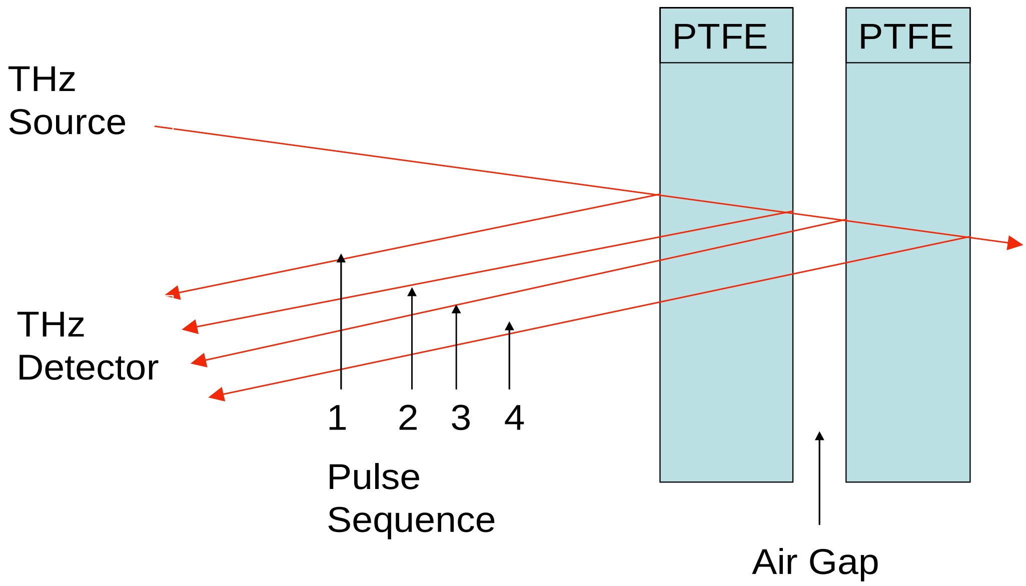

Figure 1
Experimental layout

The pulse from a typical THz source is of a complicated form, with after-runners from the effects of water vapour in the atmosphere, and delayed echoes produced in the source or detector. When this pulse is transmitted through (or reflected from) a sample this complication is compounded by the sample behaviour, and it is difficult to distinguish between the time dependence of the signal produced by the sample and that resulting from the source. An essential aspect of this method is the signal processing used to distinguish between the effects of the source and sample.

2. Pulse Reconstruction

The aim of the signal processing is to reconstruct the measured reference and sample pulses in such a way that the reference pulse becomes a simple form with a single peak. The sample pulse then becomes the response the sample would have if this simple pulse were incident upon it. The processing also reduces detection noise.

In general, for any linearly responding system the signal S(t) emerging from the sample can be written as the convolution of the source pulse F(t) with response function G(t) for the sample. The response function has the general form

$$G(t) = \sum_p A_p \delta(t - t_p).$$

The signal from the sample then has the form

$$S(t) = \sum_p A_p F(t - t_p).$$

If a linear transformation, U(t), is applied to the source pulse F(t), the transformed pulse is

$$\tilde{F}(t) = U(t) \otimes F(t).$$

Applying the same transform to the sample signal produces the reconstructed signal

$$\tilde{S}(t) = U(t) \otimes S(t) = \sum_p A_p \tilde{F}(t - t_p).$$

The reconstructed signal $\tilde{S}$ is thus the response the sample would produce to input signal $\tilde{F}$. The transformation function U is therefore devised in such a way that the source pulse is converted from a complicated form into a singly-peaked pulse with no after-runners or echoes. The width of the reconstructed source pulse determines the spatial resolution limit of depth measurement.

3. Simulated Results

A simulation of the reflected signal from the experimental phantom has been produced using recorded signals from a pulsed THz source (Figure 2). The phantom was taken to be two sheets of PTFE separated by an air gap of 100 μm. The reflected signal was simulated

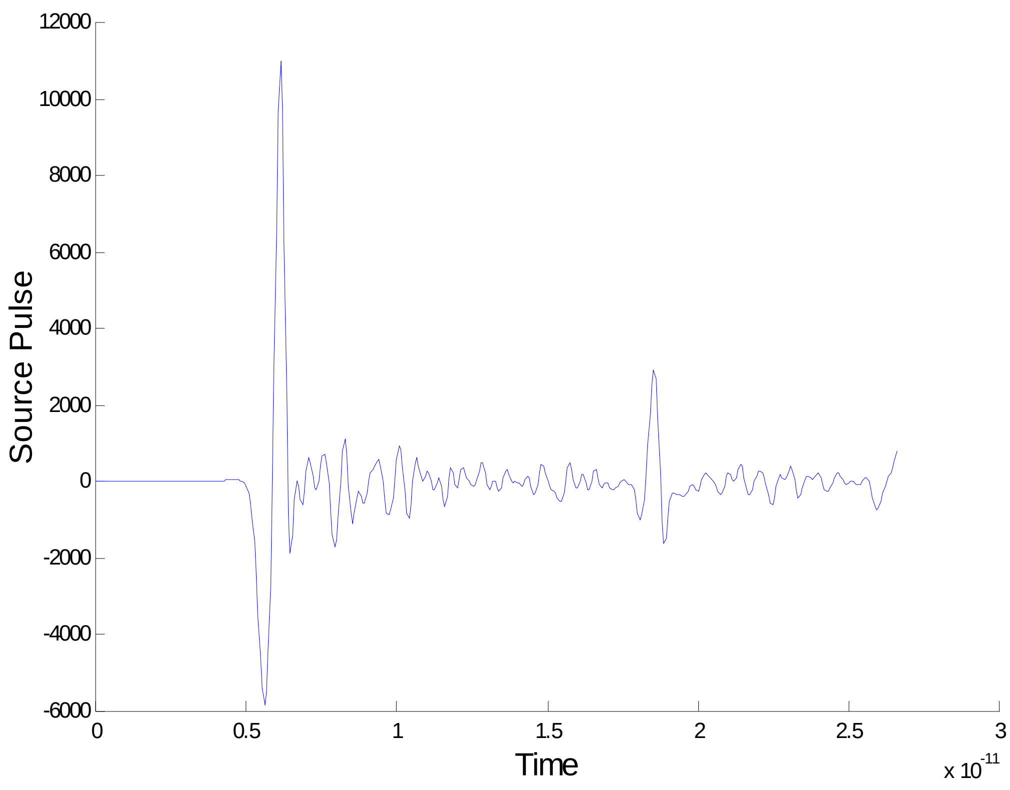

Figure 2
Typical THz pulse

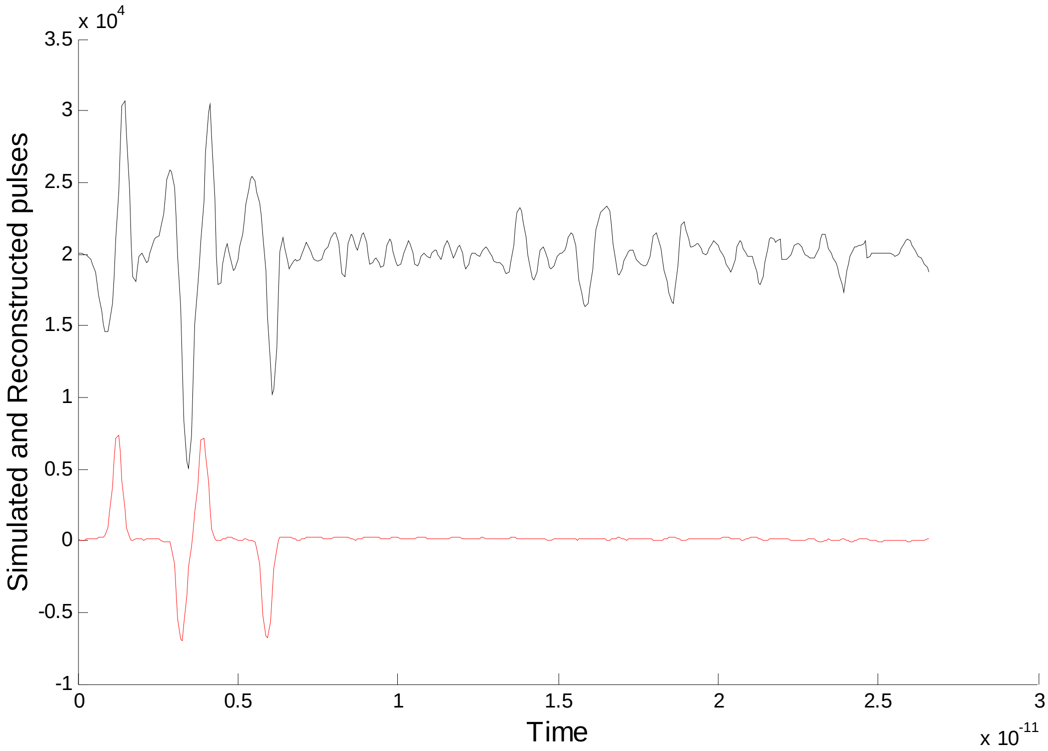

Figure 3
Simulated echo and reconstructed pulses

by adding four copies of a recorded source pulse with delays corresponding to the positions of the four surfaces (Figurer 3). The reconstructed pulses are shown in the lower trace of Figure 3, using a transformation giving a pulse width of ~0.35 ps. Clear resolution of separate pulses from the two faces of the 100 µm gap is shown.

Acknowledgements

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References

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