Measurement Notes

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Traveling-Wave THz Sampling Waveform Measurement

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Abstract

This paper discusses the possible design of a device for sampling a THz waveform. This is based on the matching of the wave velocities of the THz waveform with that of the laser pulse used to make the propagation medium conducting in a manner which makes the signal add up along a THz transmission line.

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1. Introduction

A challenging technological problem concerns the measurement of transient waveforms with picosecond (ps) resolution. Such resolution is required for oscillatory (damped sinusoidal) THz waveforms. If one has a sampling system with picosecond resolution, then one would like to extend its sensitivity by not only sampling the waveform at a particular time (analogous to a sampling oscilloscope), but perform this sampling many times, at the same time on the waveform, and adding up the sampling values.

Here we discuss an approach to this problem based on a traveling-wave sampling approach in which the usual sampling technique using a femtosecond (fs) laser which triggers a semiconductor into conduction for sub ps times (based on carrier lifetime) is generalized to a traveling-wave geometry.

2. Picosecond Sampling of Waveforms

The measurement of THz waveforms is technologically challenging. One approach for resonant waveforms (such as from switched oscillators [2]) involves correlating the waveform with the same waveform appropriately delayed [3]. This involves the measurement of energy in the pulse (approximately damped sinusoidal) formed by the sum of the waveform and its delayed form, giving reinforcement or cancellation depending on the time shift between the two waveforms. This can work to rather high frequencies since one is only measuring the energy in the summed pulse, with what can be a relatively slow detector.

An alternate approach, which is more waveform independent, involves a fast sampler of the waveform. This is analogous to a sampling oscilloscope, but operating to much higher frequencies. This has been done by various investigators (e.g., [5, 6]). Using an fs laser to make a sapphire-on-silicon switch conduct for sub ps times (it not being clear for how much smaller than 1 ps) one can measure pulse waveforms with ps widths [5]. Using an fs laser beam split into two parts, one part triggers the transmitting antenna, and the second part with appropriate variable delay (by varying length of propagation path), one can get enough samples through the waveform.

3. Traveling-Wave Picosecond Sampling

In some earlier technologies, when faced with bandwidth limitations (at the high frequency end) the high-frequency response was extended by incorporation of the structure of interest in a traveling-wave structure in which appropriate wave velocities are matched.

One example is a distributed amplifier [7]. In this device, one constructs two lumped-element transmission lines where the amplifying elements (vacuum tubes, transistors) are part of the lumped elements. The capacitances of the amplifying elements are included in the capacitive elements paired with inductors to form the line. There are two such lines with matched velocities, one for the low-level signal and the second for the amplified signal. In the second line waves are launched in both directions, The signals adding in phase in the forward direction, but out of phase (dispersed) in the backward direction, this latter wave being terminated.

Another example is the traveling-wave oscilloscope [4]. In this device the deflection of an electron beam is increased by matching the electron-beam velocity to the velocity of the electromagnetic wave along the deflection plates. The plate capacitances of a sequence of plates (along the electron beam) are matched to inductors connecting adjacent plates. As the electron beam propagates it is deflected by the first plates, and then by the second plates, etc. This increases the beam deflection for a given signal strength.

So let us consider the possibility of doing something similar with a ps sampler. As in Fig. 3.1, let us arrange two generally different dielectric media, one for the propagation of the THz beam, and a second for the propagation of the fs laser pulse. These two waves are to be matched along the THz beam so that as the fs beam makes the THz dielectric briefly conduct, the resulting signal so generated will propagate along the THz transmission line, adding up in the forward direction, but dispersed in the backward direction. This can be considered a distributed optical switch.

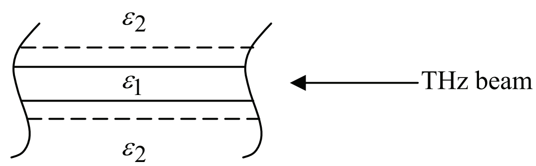
Fundamental to this concept is the two propagation velocities

$$\begin{aligned} v_{THz} &= \left[\mu_0 \varepsilon_1\right]^{-1/2} && \text{(on THz transmission line)} \\ v_{fs} &= \left[\mu_0 \varepsilon_2\right]^{-1/2} && \text{(in second dielectric)} \end{aligned} \tag{3.1}$$

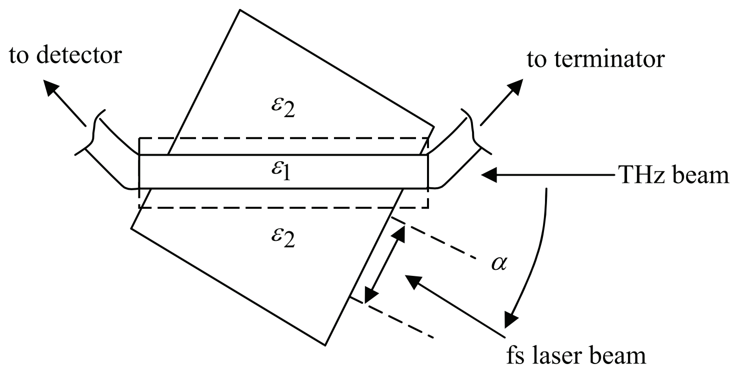
in two different media. Here the permittivities are assumed approximately constant with respect to frequency in the respective frequency domains of the THz pulse and fs laser pulse. This minimizes dispersion which would limit temporal resolution. Note that the THz beam propagates on a transmission line in the ε_2 medium. The cross-section dimensions, 2a and 2b, besides determining the characteristic impedance [1], should be small enough that only the TEM mode propagates at the THz frequencies.

Matching the two waves along the THz beam implies

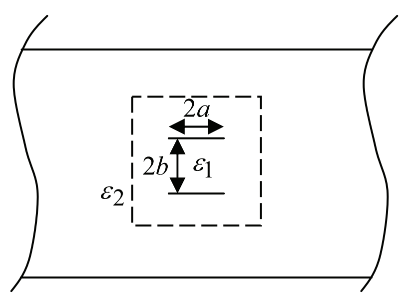
$$\begin{aligned} \cos^{-1}(\alpha) v_{fs} &= v_{THz} \\ \left[\frac{\varepsilon_1}{\varepsilon_2}\right]^{-1/2} &= \cos(\alpha) \end{aligned} \tag{3.2}$$



A. Side view



B. Top view



C. View along THz beam

Fig. 3.1 Traveling-Wave Sampling THz Device

So one needs to select two dielectric media carefully. With the velocities appropriately matched, then the fs laser pulse makes ε_2 conducting as it passes, sending waves in two directions, with coherent addition in the forward direction. The backward wave should be terminated.

The practical implication of such a detection scheme requires a favorable set of parameters. This may include sufficient fs laser power for the fan beam in the detector giving sufficient conductivity in the ε_2 medium. The lifetime of the ε_2 conduction (carrier lifetime) also needs to be sufficiently short for the desired temporal resolution.

4. Concluding Remarks

This type of traveling-wave waveform sampler is an interesting concept. However, there are many practical problems concerning its implementation. Besides the small physical dimensions, there are many issues concerning the material properties.

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