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Enhanced depth resolution in terahertz imaging using phase-shift interferometry

Jon L. Johnson, Timothy D. Dorney, and Daniel M. Mittleman[a)]
Electrical and Computer Engineering Department, Rice University, MS-366, PO Box 1892, Houston, Texas 77251

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We describe an imaging technique for few-cycle optical pulses. An object to be imaged is placed at the focus of a lens in one arm of a Michaelson interferometer. This introduces a phase shift of approximately π between the two arms of the interferometer, via the Gouy phase shift. The resulting destructive interference provides a nearly background-free measurement, and a dramatic enhancement in depth resolution. We demonstrate this using single-cycle pulses of terahertz radiation, and show that it is possible to resolve features thinner than 2% of the coherence length of the radiation. This technique could have important applications in low-coherence optical tomographic measurements. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1346626]

Imaging via time-of-flight tomography is common in many fields of research. Techniques such as optical coherence tomography (OCT)[1] have found widespread applications, in part because of their ability to image with high depth resolution. In OCT, this resolution is achieved by using a low-coherence light source, and by interfering the radiation reflected from the sample with that reflected from a reference mirror. In general, the depth resolution in such measurements is determined by the bandwidth of the radiation. This limit is a manifestation of the well-known Rayleigh criterion: it is not possible to distinguish the reflections from two closely spaced surfaces if the separation between them is much smaller than the coherence length of the light.[2] We have recently described a time-of-flight reflection imaging technique using single-cycle pulses of terahertz (THz) radiation.[3] In this case, time-domain spectroscopy permits the direct detection of the THz electric field,[4] so that the temporal separation between pulses reflected from two closely separated surfaces can be determined directly from the time-domain wave form, without interferometry. In this previous work, as in OCT, the Rayleigh criterion applies, so resolving two closely spaced reflecting surfaces is challenging.

In this letter, we describe an imaging technique that exploits interferometry to enhance the capabilities of low-coherence tomography. This technique exploits the Gouy phase shift incurred by an optical beam passing through a focus.[5] Since this phase shift is approximately equal to π, it can be used to induce a destructive interference between two single-cycle pulses. This provides a nearly background-free imaging mode and leads to a dramatic increase in the sensitivity to subtle features in a sample. The value of phase-sensitive interferometry has long been recognized as a method for improving signal-to-noise in spectroscopic measurements.[6,7] However, this is the first instance in which the Gouy phase shift is explicitly used to provide destructive interference between two arms of an interferometer. Using this method, features thinner than 2% of the coherence length can be detected.

A schematic of the interferometer is shown in Fig. 1. This is a fairly typical terahertz time-domain spectrometer, configured in a Michaelson arrangement for reflection imaging.[3,8] The terahertz pulses are generated and detected using low-temperature-grown GaAs photoconductive antennas,[9] gated with 50 fs laser pulses from a mode-locked Ti:sapphire laser. A high resistivity silicon wafer is used as a beam splitter. This wafer is 0.5 cm thick, so that multiple reflections within the beam splitter are delayed by over 150 ps relative to the initial THz pulse, and are not measured. A lens is placed in one arm of the interferometer (the sample arm), and the sample to be imaged is located at its focus. For imaging, samples are scanned in the focal spot, pixel by pixel.[8,10] The beam in the second arm of the interferometer (the reference arm) is simply retroreflected off of a flat mirror on a manual translation stage. The optical delays of the two arms are approximately equal.

In addition to providing lateral spatial resolution for imaging, the lens also provides the phase shift which permits background-free imaging. The pulse that passes through the

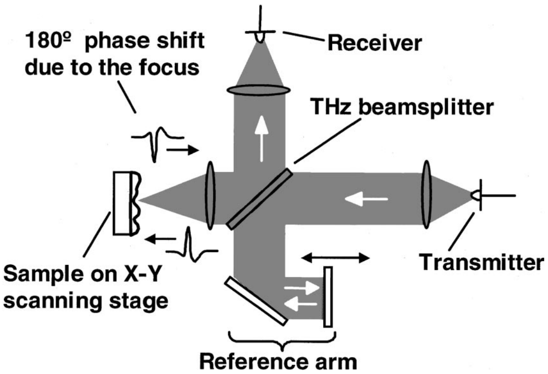

FIG. 1. Schematic of the experimental setup. The THz beam is divided by a high-resistivity silicon beam splitter. One arm (the sample arm) is focused onto the sample at normal incidence. The other arm (the reference arm) retroreflects off of a mirror on a translation stage. The THz emitter and detector are photoconductive antennas on low-temperature GaAs.

[a)] Electronic mail: daniel@rice.edu

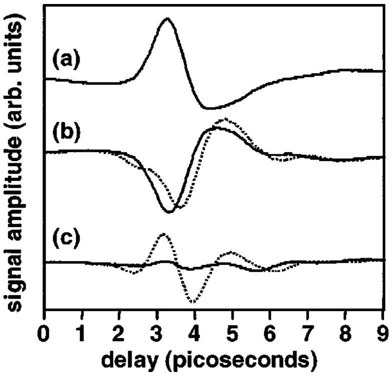

FIG. 2. Sample wave forms that illustrate the destructive interference. (a) THz wave form from the reference arm, with the sample arm blocked. (b) The solid curve shows the THz wave form from the sample arm, with the reference arm blocked. The dashed curve shows the modified wave form when a thin (45 μm) piece of adhesive tape is placed on top of the mirror. Only a small shift in delay and a very small decrease in amplitude result. (c) The solid curve shows the wave form resulting from the destructive interference of the sample and reference arms. The dashed curve shows the modification in this wave form that results from the same piece of adhesive tape. A much larger change is observed, since a small change in delay is manifested as a large change in amplitude of the interfered wave forms.

lens acquires an additional phase (compared to the pulse that traverses the reference arm) as a result of the Gouy phase shift.[11] Thus, when the pulses from the two arms of the interferometer reach the detector, they destructively interfere, and a very small signal is measured. However, if the sample contains any feature that distorts either the amplitude or phase of the reflected THz pulse, this destructive interference is disrupted and a large signal is measured. Often, it is necessary to place an aperture in the reference arm in order to adjust the amplitude of the reference pulse to be as close as possible to that of the sample arm. In a sample containing multiple reflecting layers, the reference arm delay can be positioned so as to coincide with any one of the reflections from the sample. In this fashion, it is possible to highlight subtle spatial variations in the character of buried interfaces within a composite sample.

Figure 2 shows several terahertz wave forms which illustrate this technique. Figures 2(a) and 2(b) show wave forms from the reference arm and sample arm, respectively, with a metal mirror placed in the focus of the lens. These wave forms illustrate the nearly π phase shift acquired by the sample arm, relative to the reference arm. The wave form in Fig. 2(c) shows the strong destructive interference between these two pulses resulting in a signal reduced in amplitude by more than 90%. The dashed curves in Figs. 2(b) and 2(c) illustrate the effect of introducing a small modification to the mirror in the sample arm. Here, a thin (45 μm) layer of adhesive tape has been affixed to the mirror, at the position where the THz beam is focused. The dashed curve in Fig. 2(b) shows the sample arm wave form with this perturbation in place. It indicates, primarily, a shift in arrival delay but also a small decrease in amplitude due to the absorption and index of the thin polymer layer. The dashed curve in Fig. 2(c) shows the equivalent result, with the reference arm unblocked so that the two pulses can interfere. The relative change in amplitude resulting from the perturbation is much larger in this case, since the change in arrival delay substantially disrupts the destructive interference.

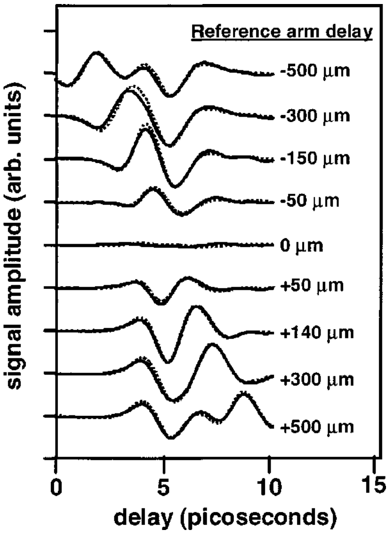

FIG. 3. The solid lines show measured interfered wave forms for various positions of the manual delay line in the reference arm, as labeled. The dashed lines show simulated results, in which the measured reference wave forms are added to a time-delayed phase-shifted replica of themselves, as described in the text. The excellent agreement indicates that the only phase distortion acquired by the beam in the sample arm is the Gouy phase shift.

We note that the interfered signal, Fig. 2(c), is not quite zero even when the sample and reference reflectors are identical. We can understand this incomplete destructive interference as a manifestation of the frequency dependence of the Gouy phase. The additional phase shift acquired by the focusing beam is given by

$$\Phi(\nu)=\pi-2\cdot\tan^{-1}\left(\frac{2\nu_c}{\nu\cdot\pi}\right),$$

where $\nu_c=fc/w_0^2$, f is the focal length of the lens and w_0 is the beam waist before the lens.[5] For frequencies larger than the critical frequency ν_c the Gouy phase shift approaches π, but for lower frequencies the confocal parameter of the focusing Gaussian beam approaches the focal length of the lens, and the phase shift rapidly drops to zero. For our experimental configuration, with a lens with $f=13.2\,\mathrm{cm}$, we estimate a beam waist of 1.5 cm and thus a critical frequency of $\nu_c=176\,\mathrm{GHz}$. Thus, a phase shift of π is not expected for all the wavelengths in the THz pulse. As a result, the interference between the sample and reference arms is not complete, and a small low-frequency wave form is measured.

We can confirm that this incomplete cancellation is responsible for the observed wave forms by measuring the interfered wave forms as a function of the delay between the sample and reference arms. In this case, both arms are reflected with identical metal mirrors. In Fig. 3, we compare these measured wave forms (solid lines) with simulated data. For these simulations, we measure the reference arm pulse, $E_{\mathrm{ref}}(\omega)$, at each delay position. We then compute the sum of this reference pulse and a delayed, phase-shifted replica of itself. That is, we plot the Fourier transform of $E_{\mathrm{ref}}(\omega)[1+e^{i\omega\tau}\cdot e^{i\Phi(\nu)}]$ for each position of the delay stage. This simulates the coherent superposition of the reference and sample arms, using only the retroreflected reference arm as an input. The excellent agreement between the measurements and simulations indicates that the Gouy phase is sufficient to explain the observed wave forms.

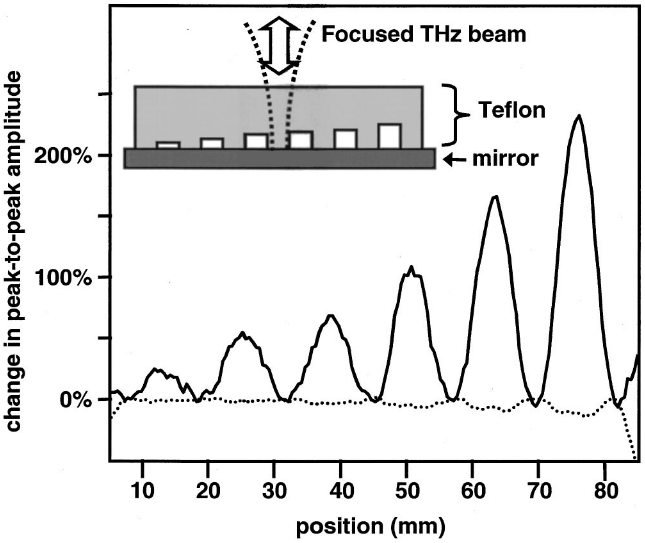

FIG. 4. Line scans of a model structure with machined air gaps ranging in thickness from 12.5 to 100 μm. The inset shows a schematic of this sample. The line scans are shown as relative changes in the peak-to-peak amplitude of the wave forms as a function of position across the sample. Without interferometry, (dashed curve) only the largest air gap can be discerned. However, the interferometric case (solid) shows a dramatic increase in contrast, demonstrating the ability to detect the smallest (12.5 μm) gap. These measurements were performed with fairly long THz pulses, with a coherence length of approximately 0.8 mm.

Figure 3 emphasizes the distinction between our imaging technique and conventional optical coherence tomography. In OCT, the measurement variable is the delay of the reference arm. It is necessary to obtain data at many different reference arm positions in order to determine the electric field of the pulse train reflected from the sample.[1] In our measurements, a complete wave form can be measured at any reference arm delay since the THz electric field is measured directly. This permits us to exploit the destructive interference in a manner which is not currently possible at optical frequencies.

For the measurements shown in Fig. 3, the coherence length of the THz pulse is about 0.8 mm. We note that, for delays less than half of the coherence length of the pulse, it is difficult to discern two pulses in the wave forms. The resulting wave forms are quite complex, exhibiting evidence of both constructive and destructive interference. This results in a large range of peak-to-peak amplitudes, from nearly zero to almost twice the peak-to-peak amplitude of the original pulse. We note that previous THz imaging experiments have demonstrated a high degree of sensitivity to small shifts in the delay of the measured pulse.[8] The interferometric technique converts these small delay shifts into relatively large amplitude shifts, with a corresponding increase in sensitivity. It also permits us to detect two closely spaced surfaces, which would ordinarily generate little or no reflection signal due to destructive interference.[3]

To demonstrate this latter ability, we have constructed a model sample containing a series of thin well-controlled features. The inset in Fig. 4 shows a schematic of this teflon–metal model, with air gaps between the two pieces ranging from 12.5 to 100 μm in width. We image a line scan across this sample, and compare the results with and without the interferometric cancellation. The results are shown in Fig. 4 as the percent change in peak-to-peak amplitude of the measured wave forms, relative to a wave form measured on a spot that does not contain an air gap. The contrast of the interferometric signal is enhanced by an order of magnitude over the noninterferometric signal. Without the reference arm almost no change in amplitude is observed and only the largest air gaps can be detected. In the interferometric mode the areas with no air gap show strong destructive interference. The change in the cancellation when an air gap is encountered results in a large increase in contrast. As a result, it is possible to detect the smallest air gap using the interference effect. This 12.5 mm gap is roughly 80 times smaller than the coherence length of the terahertz pulses used to collect the data of Fig. 4.[12]

In conclusion, we have described an imaging technique which uses the Gouy phase shift to provide a destructive interference between two arms of an interferometer. This, in turn, permits a nearly background-free method for imaging with a corresponding dramatic contrast enhancement for subcoherence length features in a sample. This phase-shift interferometry permits imaging well below the conventional Rayleigh bandwidth limit. Since the Gouy phase is a geometric phase, and is a very general phenomenon, this technique is not limited to THz imaging. In any situation where few-cycle pulses are available, this phase-shift method can provide substantial improvements in depth resolution. With recent advances in femtosecond pulse techniques,[13] it could find important applications in optical imaging methods such as coherence tomography.

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