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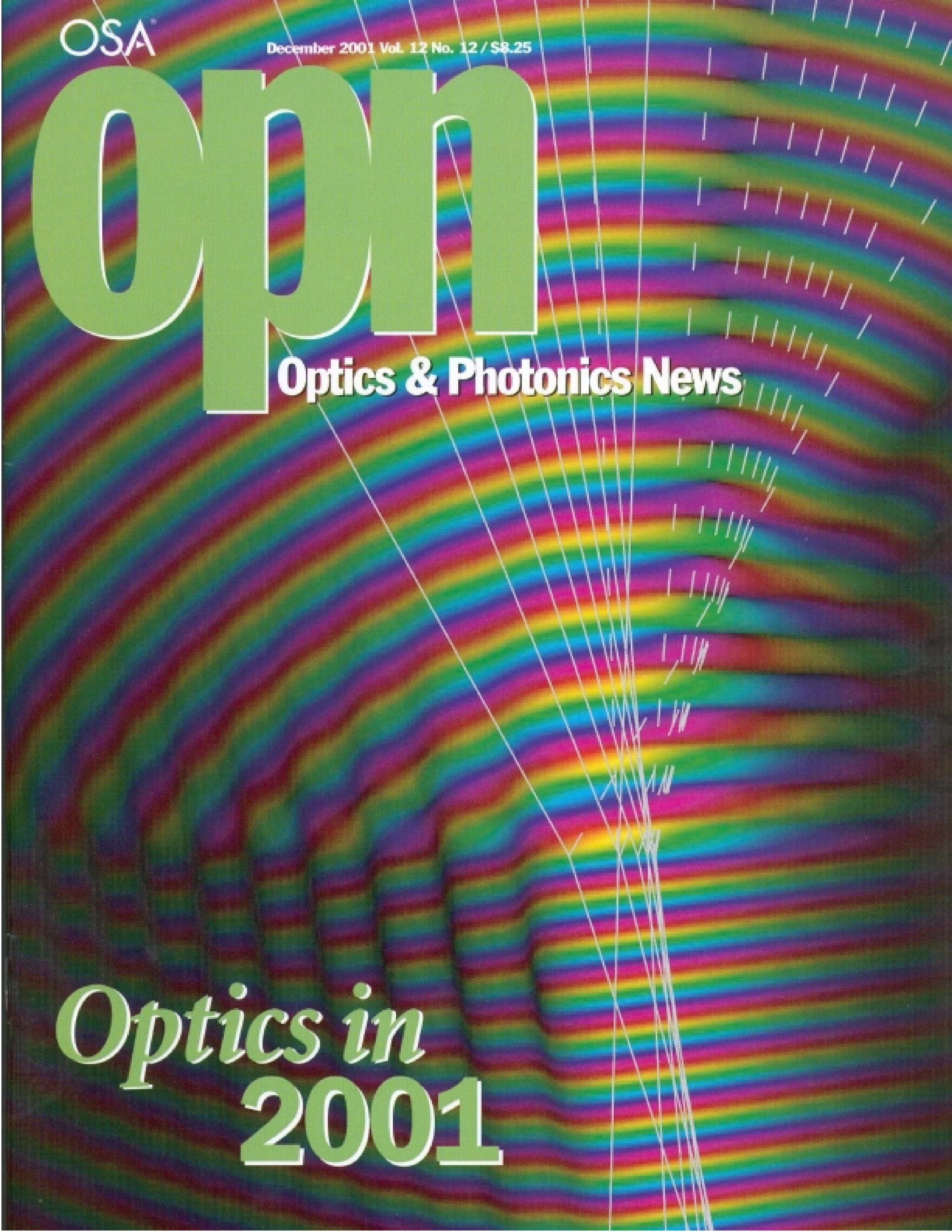

Optics in 2001

IMAGING

Enhanced Depth Resolution Using Phase-Shift Interferometry

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Imaging by way of 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 by use of interferometry. 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. Recent advances in ultrafast optoelectronics have led to the development of a time-of-flight reflection imaging technique using single-cycle pulses of terahertz (THz) radiation.[2] In this case, time-domain spectroscopy permits the direct detection of the THz electric field, so interferometry is not required. Nevertheless, as in OCT, the Rayleigh criterion applies, so resolution of two closely spaced reflecting surfaces is a challenge.

We describe a new technique that combines coherent detection with interferometry to beat the Rayleigh limit, and we demonstrate it using THz time-domain spectroscopy. The single-cycle THz pulses, generated and detected by use of conventional photoconductive sampling methods,[3] are injected into a Michaelson interferometer. A lens is placed in one arm of the interferometer (the sample arm), and the sample to be imaged is located at its focus. 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.

In addition to providing transverse spatial resolution for imaging, the lens also provides the phase shift that permits background-free imaging. The pulse that passes through the lens acquires an additional phase of approximately π (compared to the pulse that traverses the reference arm) as a result of the Gouy phase shift.[4] Thus, when the pulses from the two arms of the interferometer reach the detector they destructively interfere, and a small signal is measured. However, if the sample contains any feature that distorts either the amplitude or the phase of the reflected THz pulse, this destructive interference is disrupted and a large signal is measured.

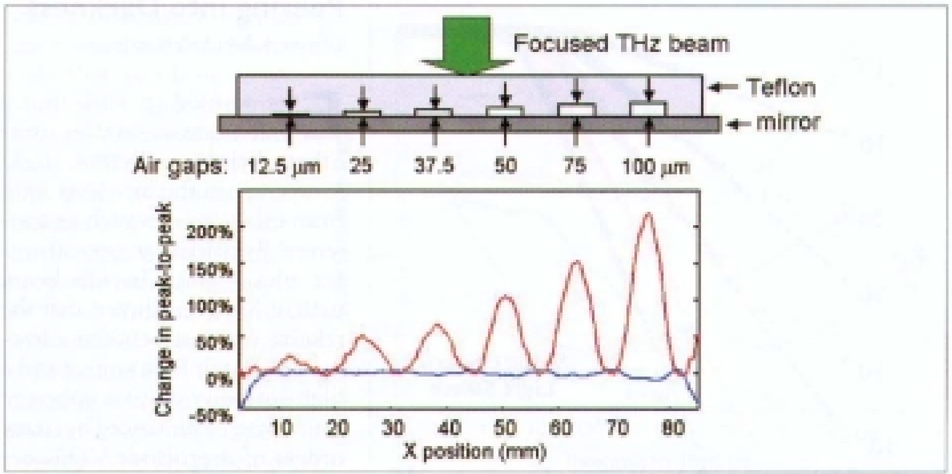

Figure 1. The upper part of the figure shows a schematic cross-section of a model sample, with a series of air gaps between Teflon and a metal mirror of calibrated width. The lower part represents two line scan images across this sample, showing the peak-to-peak amplitude of the reflected THz pulse as a function of position across the sample, both with (red) and without (blue) interferometry. In these data, the coherence length of the THz pulse is about 80 times larger than the smallest air gap (12.5 µm).

The figure shows an example of the enhanced contrast provided by phase-shift interferometry. The upper part of the figure shows a schematic cross-section of a model sample, consisting of a Teflon-metal sandwich with a series of calibrated air gaps. The data represent two line-scan images that show the percent change in amplitude of the measured THz waveform as a function of lateral position across the sample. The blue curve shows the result with conventional reflection imaging,[2] whereas the red curve shows the dramatic contrast enhancement resulting from the interferometric technique. In these measurements, the thinnest air gap is approximately 80 times smaller than the coherence length of the THz pulses. This technique dramatically broadens the applicability of THz imaging to samples with features well below the Rayleigh limit. Moreover, since the Gouy phase is a purely geometric effect, this result is applicable to any situation in which a field is coherently detected.

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