Polarization-sensitive air-biased-coherent-detection for terahertz wave

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Employing an orientation-modulated bias field, a polarization-sensitive scheme for terahertz air-biased-coherent-detection (THz-ABCD) is presented to directly measure the amplitude and polarization angle of THz field in the time domain. It can provide all characteristics of arbitrarily polarized THz wave with one single-scan measurement. Measuring convenience, broad bandwidth, and high angular resolution have been achieved. Polarization-sensitive THz time-domain spectroscopy can surely be developed based on this technology. Many other applications in the THz spectral region are also believed. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4748171]

Terahertz time-domain spectroscopy (THz-TDS), which is sensitive to the material effects on both the amplitude and the phase of THz radiation, provides more information than conventional Fourier-transform spectroscopy.[1] Now, it is widely used in many fields, such as material characterization,[2] ultrafast dynamic process study,[3] and biological science.[4]

The measurement of pulsed THz radiation, which is based on the sampling technology,[5] uses the concept that the field of THz wave can be considered static for each single probe pulse, and the temporal waveform can be reconstructed from the samples probed with different time delays. Although each sample should be described by both the field amplitude and the polarization angle, most of the measuring techniques are not polarization-sensitive because of the linearly polarized detectors. Some previous works have been made to obtain the polarization information, in which the two orthogonal components of THz radiation have been measured, successively[6,7] or simultaneously.[8,9] The polarization angle of THz field can be deduced. However, the electric devices and the optical arrangements are complicated. Measuring deviation can easily be introduced by the separate signal processings or any change of the optical circuit.

In this letter, we present a polarization-sensitive scheme of air-biased-coherent-detection (ABCD) for THz-TDS to directly measure the amplitude and polarization angle of the THz wave, which efficiently eliminates the measuring deviation of the two orthogonal components. The amplitude and the polarization angle of THz wave, as well as the two orthogonal components can be obtained just with one single scan.

Unlike asymmetric materials used in electro-optical sampling, THz-ABCD uses gases as the nonlinear media and utilizes the third-order optical nonlinearities. An amplitude-modulated bias field is necessary to overlap the THz field. The THz field amplitude is measured using heterodyne detection.[10] The similar concept is employed in our scheme. An orientation-modulated bias field is used here to measure the THz amplitude and polarization simultaneously. The schematic diagram resembles that of the conventional ABCD but circularly polarized laser beam and rotating bias field are employed. As shown in Fig. 1, a broad-bandwidth quarter wave plate has been used and two orthogonally arranged pairs of electrodes are located just at the focus of the probe beam. The electrode pairs are provided with sine-wave voltage and cosine-wave voltage separately, which leads a rotating bias field in the normal plane of the probe beam. As shown in the inset of Fig. 1, a probed sample is selected for the following discussion. The amplitude $E_{\rm THz}(\tau)$ and the polarization angle $\theta_{\rm THz}(\tau)$ are supposed, where τ is the probe delay.

For a nonlinear-optical estimation of the second-harmonic (SH) yield, Cartesian coordinates rotating with the composite field are defined. As sketched in Fig. 2, $E_{\rm bias}$ and Ψ are the amplitude and angular velocity of the bias field, respectively. Obviously the composite field E_Σ satisfies $E_\Sigma^2 = E_{\rm bias}^2 + E_{\rm THz}(\tau)^2 + 2E_{\rm bias}E_{\rm THz}(\tau)\cos(\Psi t - \theta_{\rm THz}(\tau))$. Since the third-order susceptibility tensors of gases are employed,[10,11] four non-zero components should be concerned here, i.e., $\chi^{(3)}_{xxxx}$, $\chi^{(3)}_{xxyy}$, $\chi^{(3)}_{yxxy}$, $\chi^{(3)}_{yyxx}$ (the four subscripts are corresponding to the components of SH, THz or bias field, fundamental harmonic, and

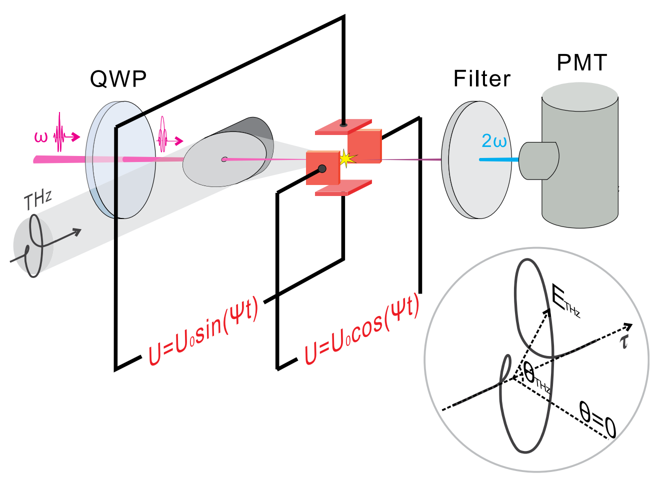

FIG. 1. The scheme of polarization-sensitive ABCD. QWP: broadbandwidth quarter wave plate; PMT: photomultiplier tube.

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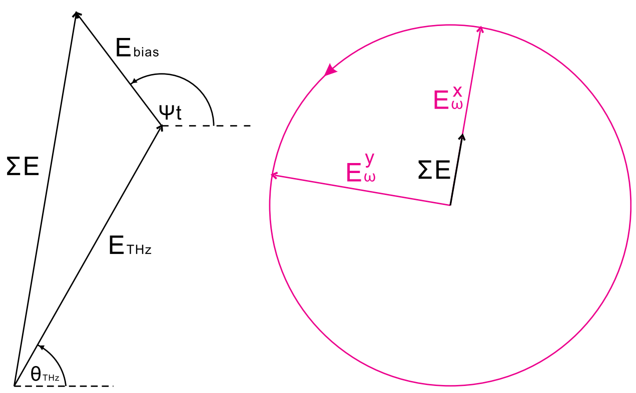

FIG. 2. The sketch of composite field (left) and the rotating coordinates (right).

fundamental harmonic, respectively). In the case that the carrier-envelope phase (CEP) of the laser pulse can be neglected (the CEP is not locked or the pulse has a long duration, e.g., tens of times longer than the laser period), the circularly polarized laser pulse is centrosymmetric averagely, i.e., $E^y_\omega = E^x_\omega e^{i\pi/2}$. The two components of the SH can be expressed as

$$E^x_{2\omega} \propto \chi^{(3)}_{xxxx} E_\Sigma E^x_\omega E^x_\omega + \chi^{(3)}_{xxyy} E_\Sigma E^y_\omega E^y_\omega \propto (\chi^{(3)}_{xxxx} - \chi^{(3)}_{xxyy}) E_\Sigma I_\omega \quad (1)$$

and

$$E^y_{2\omega} \propto \chi^{(3)}_{yxyx} E_\Sigma E^y_\omega E^x_\omega + \chi^{(3)}_{yxxy} E_\Sigma E^x_\omega E^y_\omega \propto (\chi^{(3)}_{yxyx} + \chi^{(3)}_{yxxy}) E_\Sigma I_\omega e^{i\pi/2}. \quad (2)$$

The intensity of the SH follows

$$I_{2\omega} \propto |E^x_{2\omega}|^2 + |E^y_{2\omega}|^2 \propto E^2_\Sigma. \quad (3)$$

Although the above analysis for the SH yield based on perturbation theory may be disputed if the laser intensity is strong enough to ionize gases, according to the spatial symmetrical characteristic and the previous experimental results,[10] the dependence of SH yield on THz field will keep well accordance with Eq. (3).

In the scheme, a photomultiplier tube (PMT) is employed to detect the SH. For its slow response, the SH can be considered instantaneous and therefore the SH intensity in the time domain obeys

$$I_{2\omega}(t) \propto \delta(t_k) E^2_\Sigma = \delta(t_k)[{E_{\rm bias}}^2 + E_{\rm THz}(\tau)^2 + 2E_{\rm bias}E_{\rm THz}(\tau)\cos(\Psi t - \theta_{\rm THz}(\tau))], \quad (4)$$

where t_k is the moment that the kth SH pulse illuminates the PMT and $\delta(t)$ is the delta function. Since the laser pulses are periodical, the expression in Eq. (4) can be considered as a sampling result whose sampling frequency is equal to the laser repeated frequency $F_{\rm Laser}$. According to the Nyquist-Shannon sampling theorem, the information described by the right term can be reserved in the case $F_{\rm Laser} > \Psi/\pi$. If a lock-in amplifier is employed and the cosine-wave voltage synched with the bias voltages is selected as the reference, the measured SH intensity can be expressed as

$$I_{2\omega}(t) \propto E_{\rm bias}E_{\rm THz}(\tau)\cos(\Psi t - \theta_{\rm THz}(\tau)). \quad (5)$$

In most detection schemes for THz-TDS, lock-in amplifiers are used to measure the amplitude of THz field. Although in many cases, only the signal amplitude is concerned, dual-phase lock-in amplifier can simultaneously output the amplitude, the phase, and the two components with $\pi/2$ phase difference. Here, this instrument is employed to demonstrate our concept. As the synchronous reference signal is used, the amplitude $E_{\rm THz}(\tau)$ and the polarization angle $\theta_{\rm THz}(\tau)$ are obtained. All information of THz wave in the time domain can be acquired with just one single scan.

In our experiment, a commercial femtosecond laser amplifier is employed, which is seeded by a 78 MHz femtosecond oscillator and produces 26 fs pulses with a repeated frequency of 1 kHz. A 100 μm thick β-BBO (beta-barium borate) crystal for ooe-type interaction is used to achieve ionizing two-color laser beams, whose optical axis is oriented at 45° angle with respect to the polarization direction of the probe beam. The laser beams are focused by a parabolic mirror for terahertz generation. Since the polarization analysis of THz emission is beyond the scope of this paper, here we just employ it as a source. In the detection section, two 250 Hz alternating signals with $\pi/2$ phase difference are generated by two direct-digital-synthesis (DDS) chips using the oscillator sync signal as the clock. After filtration and amplification, these signals are stepped up to high voltages with amplitudes up to 8 kV (transformers dependent) and then employed to introduce the rotating electric field. Another cosine-wave signal, which is filtered and amplified directly from the DDS output, with amplitude of 5 V and synchronous phase with the high voltages, is used as the reference of the lock-in amplifier.

Fig. 3 shows the measuring results of the elliptically polarized THz pulse. The time-domain waveform of THz field is shown as a 3D plot. Both orthogonal components and the polarization information are also plotted for clarification in the figure. The spectra of the two components are shown in Fig. 4, which indicate that the broad bandwidth (from 0.3 to 30 THz, source and laser pulse duration dependent) have covered the "terahertz gap."

Measurements have also been done employing the conventional ABCD scheme for comparison. The results are in

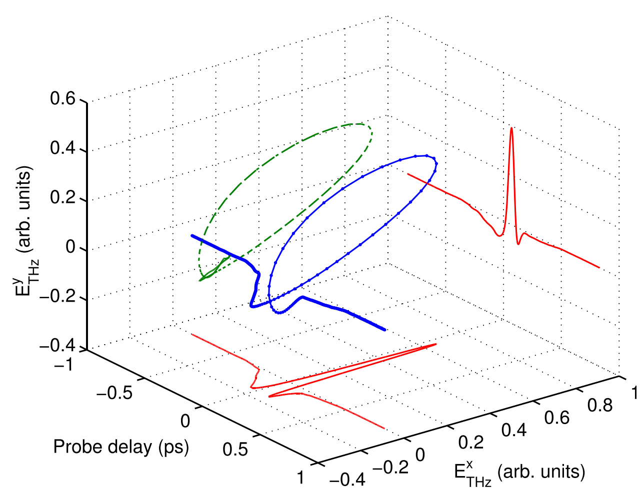

FIG. 3. The measuring result of an elliptical polarized THz wave. The orthogonal components and the polarization information are also shown as cast shadows in the figure.

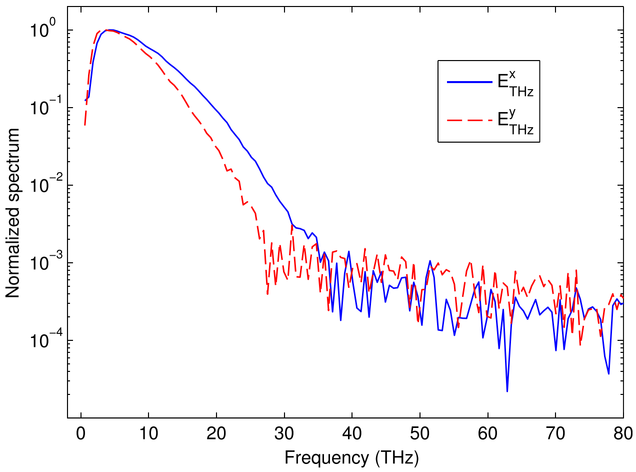

FIG. 4. The normalized spectra of the two orthogonal components of THz field.

well-accordance, but the signal amplitudes of the conventional ABCD are about twice larger if the bias fields with same amplitudes are used. The signal-to-noise ratios (SNRs) of the two different schemes, unexpectedly, are approximately equal in our experiment.

In the process of THz detection, 20 times repeated measurements with intervals of 10 s have been made for every scan step. Not peak amplitude but the amplitudes of selected steps are used; dynamic range (DR) and SNR are defined for the steps consulting Ref. 12. The average values of the polarization angles $\bar{\theta}$ and the measuring errors $\Delta\theta$ have been shown in Table I, where the tolerance of the lock-in amplifier is ignored. The calculated angle errors $\Delta\theta_{cal}$ based on the two orthogonal components measured by the conventional ABCD are also listed, which are all a bit larger. It suggests that the noises in the two components are not independent, and high angular resolution can be achieved employing our scheme.

Although the angular resolution is determined by the DR and SNR theoretically, the mechanism of the lock-in amplifier should be noted. Another group of data are shown in Table I as a phase shift θ_{shift} of 90° is set to the reference in the lock-in amplifier, which indicate that an appropriately selected phase shift between the reference and bias field can significantly improve the angular resolution for a specified angular direction. It is because that the outputted angle is a deduced value utilizing the inverse tangent function. Its error is associated with its value.

TABLE I. The angle errors of several points in time domain.

DR	SNR	$\bar{\theta}$	$\Delta\theta(\theta_{shift}=0)$	$\Delta\theta_{cal}$	$\Delta\theta(\theta_{shift}=90°)$
135	43	56°42′	46′	64′	1°48′
287	50	56°27′	22′	52′	51′
569	52	−107°30′	5′	22′	49′
961	55	−111°54′	4′	26′	24′
75	35	5°15′	>18°	>24°	10′

In conclusion, we have presented a polarization-sensitive scheme for THz-ABCD, which can provide all information of THz pulse with the similar usage of the common sampling technology. The polarization status can be obtained more conveniently and accurately. The merit of broadband detection is demonstrated. It is also important that it can be easily improved from the conventional scheme. As the generation of the THz wave with arbitrary polarization has been in control,[13] wide applications of this polarization-sensitive ABCD are surely believed.

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