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# Fast determination of terahertz polarization azimuth angle based on the core-anti-resonant effect

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Yangjun Mei,<sup>1</sup> Yifu Tian,<sup>1</sup> Yongpeng Han,<sup>1</sup> Li Lao,<sup>2</sup> and Jiayu Zhao<sup>1,3,a)</sup> 

## AFFILIATIONS

<sup>1</sup>Terahertz Technology Innovation Research Institute, Terahertz Spectrum and Imaging Technology Cooperative Innovation Center, Shanghai Key Lab of Modern Optical System, University of Shanghai for Science and Technology, Shanghai 200093, China

<sup>2</sup>Tera Aurora Electro-optics Technology Co., Ltd, Shanghai 200093, China

<sup>3</sup>Shanghai Institute of Intelligent Science and Technology, Tongji University, Shanghai 200092, China

<sup>a)</sup>Author to whom correspondence should be addressed: [zhaojiayu@usst.edu.cn](mailto:zhaojiayu@usst.edu.cn)

## ABSTRACT

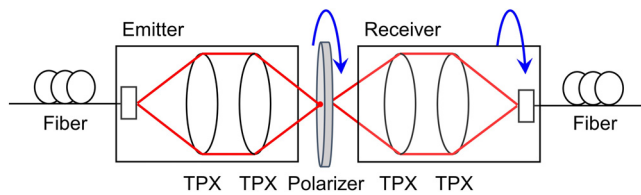
The azimuth angle of linearly polarized light plays a crucial role in optical mechanism investigations and various applications. However, in the terahertz (THz) band, traditional detection methods suffer from low efficiency or require complex apparatus. In this work, based on the core-anti-resonant reflection (CARR) principle, we propose a polarization-sensitive CARR cavity, namely, a simple 3D-printed tube with an Archimedean spiral structure of the cross section, which links the input linear polarization azimuth angle to the output resonant frequencies. In this way, the spatial polarization angle can be rapidly resolved via the Fourier-transformed THz spectrum from the detected single THz temporal pulse. Therefore, the experimental system configuration is simplified, and more importantly, the detection efficiency has been significantly enhanced.

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The detection of linear polarization azimuth angle in different electromagnetic frequency scales is important for various applications. For example, the linear polarization azimuth angle has been measured to provide information for navigation in the skylight band,<sup>1,2</sup> and to precisely detect the glucose solution concentration with a He–Ne laser wavelength.<sup>3</sup> Yao *et al.* demonstrated the application of linear polarization at different azimuth angles of the ground-to-zenith light (in the range of 400–900 nm) in the satellite remote sensing of the earth's surface.<sup>4–6</sup> Additionally, Ding *et al.* applied the gigahertz linear polarization azimuth angle in wireless communications.<sup>7</sup> Specifically, in the terahertz (THz) band, since strong THz sources<sup>8–15</sup> prefer to radiate linearly polarized THz waves, the corresponding azimuthal angles also carry fruitful physical information for exploring the properties, mechanisms, and optimization methods of THz-optical processes. For instance, the azimuth angle of linearly polarized THz wave has been employed to investigate the physical mechanisms of laser plasma radiation in the THz range,<sup>16</sup> to study the Faraday rotation effect in graphene<sup>17</sup> and in doped silicon,<sup>18</sup> as well as to examine the Hall mobility in doped semiconductors,<sup>19</sup> and to assess the linear polarization rotation performance of metasurface devices,<sup>7,20</sup> among others.

Therefore, simple, fast, and accurate detection methods of the THz linear polarization azimuthal angle are particularly important. Currently, the most direct way is to rotate a THz polarizer for 360° to scan THz signals of different linear polarization orientations, for example as illustrated in Fig. 1, by inserting a THz polarizer (e.g., metal wire grid) between the THz photoconductive antenna (PCA) emitter and receiver. In addition, the polarizer can also be rotated between the horizontal and vertical directions in order to acquire two orthogonal THz time-domain signal components. Subsequently, by plotting the THz polarization state diagram, its polarization azimuth angle can be determined. Furthermore, due to the polarization dependence of the detection PCA, it has to be rotated along with the polarizer. Alternatively, if the electro-optic sampling (EOS) scheme is used to detect the THz wave, the EO crystal can also be rotated instead of the THz polarizer.<sup>21</sup> However, a high-speed rotation of the optical device would bring measurements with additional mechanical errors.<sup>6</sup>

In addition, fast THz polarization measurements can also be achieved by periodically modulating the probe polarization via photoelastic (PE) or EO methods<sup>22,23</sup> during the pump-probe (THz-laser) experiments. However, these methods theoretically cannot surpass the



**FIG. 1.** Schematic diagram of a conventional detection setup for the THz polarization azimuth angle based on the THz PCAs, where the four TPX are THz lenses.

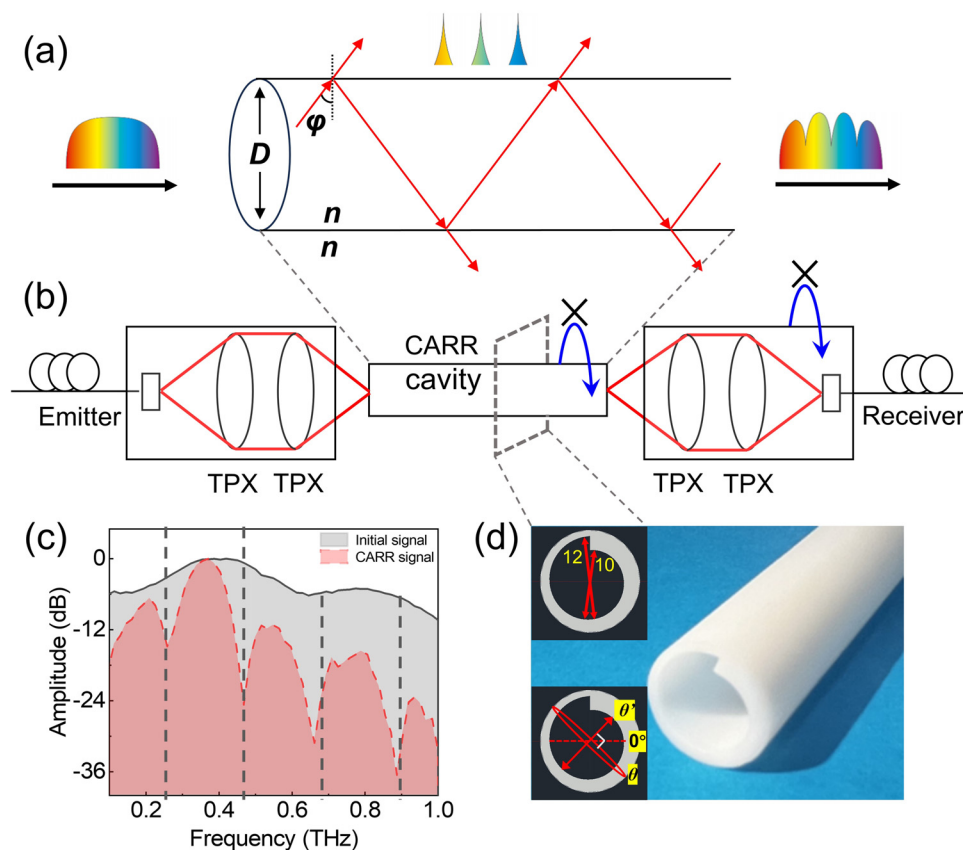
frequency limitations imposed by the electrical technique, whose modulation frequency might only reach up to the gigahertz range, corresponding to a timescale of nanoseconds. Hence, this method is clearly not suitable for diagnosing transient THz-optical processes, e.g., acquiring the polarization information from low-repetition-rate or even single-shot THz sources.

Furthermore, the simultaneous detection of orthogonal polarization components has also been proposed in order to restore the initial THz polarization state. For example, one can adopt a PCA detector with orthogonal slits<sup>24,25</sup> or combine a THz polarization splitter with two EOS systems.<sup>26–28</sup> However, the former can still not achieve fast measurements at the single-shot level, and the latter requires a

substantial number of optical devices, which not only inevitably introduces energy losses into the beam paths and decreases the signal-to-noise ratio (SNR), but also seems too complex for the specific goal of determining the THz polarization azimuth angle.

In this work, we proposed an efficient method to achieve the THz linear polarization azimuth angle within the time of detecting a single THz pulse and only utilized a 3D-printed Archimedean spiral tube with varied inner diameters acting as the THz modulator. Briefly, the input azimuth angles ( $\theta$ ) of linearly polarized THz beams can be encoded in the form of resonant frequencies ( $f_m$ ) in the transmitted THz spectrum along the Archimedean spiral tube, based on the principle of core-anti-resonant reflection (CARR) effect. As a result, one can easily distinguish between different  $\theta$  according to different  $f_m$  of the output frequency-domain THz signal. Hence, this scheme only requires the detection of a single modulated THz temporal pulse, from which the THz spectrum and its  $f_m$  can be immediately obtained by Fourier transformations.

The principle of CARR<sup>29–32</sup> is illustrated in Fig. 2(a). When the broadband THz wave is incident into a thin-walled tube, it undergoes Fabry-Pérot-like (F-P-like) oscillations within the tube core. During this process, the frequency components, which resonate with the F-P cavity, transmit through the tube wall, while the anti-resonant components remain confined along the tube. This ultimately results in



**FIG. 2.** (a) Schematic of the CARR effect inside a F-P-type tubular cavity. (b) The experimental setup for rapid determination of the linear polarization azimuth angle. (c) Spectra of the initial THz signal and output CARR signal. (d) The structure of the designed Archimedean spiral tube (numbers in unit of mm).

periodic dips on the THz spectrum output from the CARR tube, and the spectral positions of these resonant frequency ( $f_m$ ) correspond to  $f_m = \frac{mc}{2nD\cos\varphi}$ , where  $m = 1, 2, 3, \dots$  is the resonance order,  $c$  is the speed of light in vacuum,  $n$  is the refractive index inside the hollow core (here  $n = 1$  for air),  $D$  is the inner diameter of the tube, and  $\varphi$  is the incidence angle of THz waves on the inner surface of the tube.

To experimentally verify this CARR effect, a common tube was made of polyethylene (PE) by 3D printing (3DSL-800, Crealty) with the inner diameter of 12 mm, wall thickness of 0.85 mm, and length of 15 cm. Then, it was mounted into our all-fiber THz time-domain spectroscopy system (THz-TDS), partly as shown in Fig. 2(b). Briefly, the PE tube acted as a THz modulator between the PCA emitter and receiver (TERA 15-TX-FC, TERA 15-RX-FC, Menlo Systems), and four TPX lenses assisted the system by collimating or focusing the THz beam. Meanwhile, the PCA emitter and receiver were stimulated by a femtosecond laser (LangYanTech) with the following parameters: 1560 nm (central wavelength), 120 fs (pulse duration), 60 mW (average power), and 100 MHz (repetition rate). Furthermore, to ensure the equal optical lengths between the pump and probe paths, an optical delay line was installed in the probe path. Figure 2(c) depicts the initial frequency-domain THz signal and the output CARR signal. It can be observed that the latter exhibits four dips along vertical dashed lines (equally spaced), consistent with the theoretical predictions as shown in Fig. 2(a). The average dip interval is about 0.232 THz, which is close to the calculated value of 0.239 THz given by the  $f_m$  formula with  $D = 12$  mm and  $\varphi = 87^\circ$ . Note that the THz spectra in Fig. 2(c) were Fourier-transformed from the THz temporal pulses (please see Discussions before Conclusion of this work) recorded by our THz-TDS system.

In view of the  $f_m$  formula, it is possible to connect the spectral resonant frequency interval ( $\Delta f$ ) with the inner diameter ( $D$ ) via

$$\Delta f = \frac{c}{2D \cos \varphi}. \quad (1)$$

Based on this relationship, if  $D$  could be continuously varied along different azimuth angles ( $\theta'$ ), then an arbitrary linearly polarized THz wave can find its exclusive  $D$  and  $\Delta f$ , in which way the polarization azimuth can be retrieved from the THz spectrum. Therefore, we designed an Archimedean spiral tube with  $D$  ranging from 10 to 12 mm as displayed in Fig. 2(d), whose inner radius  $r$  is calculated as follows:

$$r(\theta') = a + b\theta', \quad (2)$$

where  $a$  and  $b$  are two constants. By further defining  $D_{\min} = 10$  mm at  $\theta' = -90^\circ$  and  $D_{\max} = 12$  mm at  $\theta' = 90^\circ$ ,  $a$  and  $b$  can be obtained by resolving the following equation groups:

$$\begin{cases} r_{-90} + r_{90} = 10 \\ r_{90} + r_{270} = 12 \end{cases} \quad \begin{cases} r_{-90} = a + b \times (-90) \\ r_{90} = a + b \times 90 \\ r_{270} = a + b \times 270. \end{cases} \quad (3)$$

The resultant  $a$  and  $b$  are 5 and  $1/180$ , respectively. Please see also the supplementary material S1 for the reason for the selection of  $D = 10$ –12 mm, and another cross-sectional structure design of our CARR tube beyond the used Archimedean spiral. In this work,  $\theta$  and  $\theta'$  indicate the azimuth angles of the input THz linear polarization and the connected  $D$  diameter, respectively, as shown in the inset of Fig. 2(d). The relationship of  $\theta' + 90 = \theta$  is always maintained. This is

due to the TE dependence of the THz wave during CARR-type oscillations inside the tube,<sup>29</sup> which means a THz pulse polarized along  $\theta = 0^\circ$  corresponds to the perpendicular  $D$  along  $\theta' = -90^\circ$ .

Finally, the manufacturing method and material of the tube remain 3D printing and PE, and the experimental Archimedean spiral tube is shown in Fig. 2(d). Next, we inserted the Archimedean spiral tube into the experimental setup as shown in Fig. 2(b) to verify its validity of distinguishing different azimuth angles of linearly polarized THz waves passing through it.

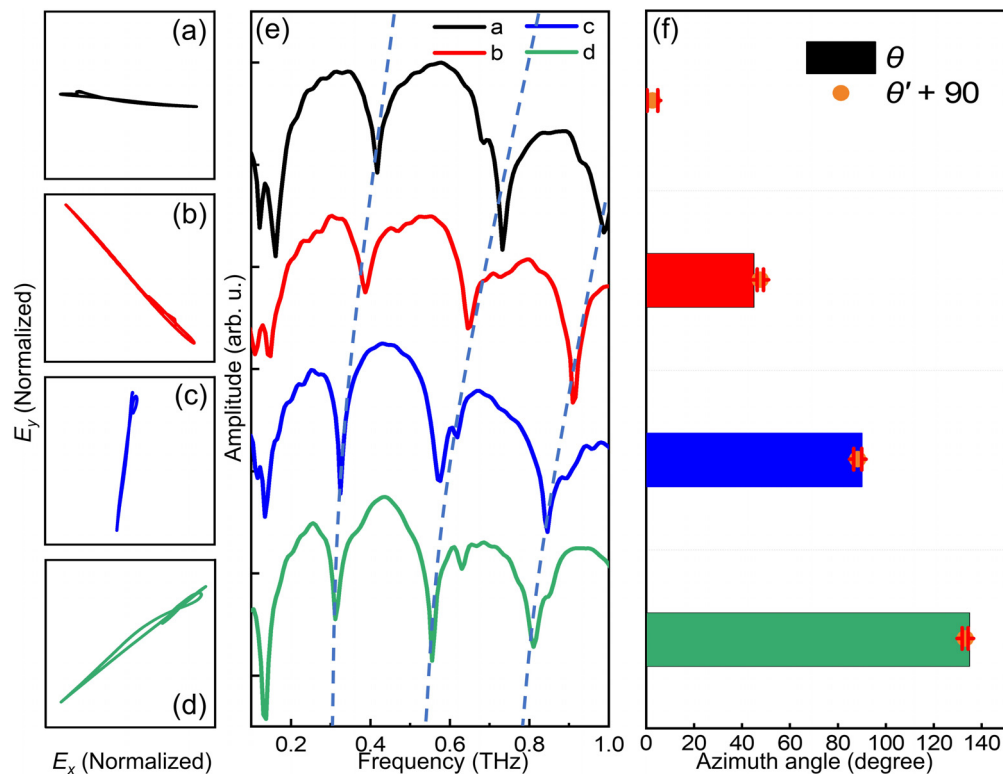
We employed the experimental setups displayed in Figs. 1 and 2 to measure the THz linear polarization azimuth angles of  $0^\circ$ ,  $45^\circ$ ,  $90^\circ$ , and  $135^\circ$ , with the results depicted in Figs. 3(a)–3(d) and 3(e), respectively. It can be observed that Figs. 3(a)–3(d) represent the THz linear polarization states, each of which is synthesized from two orthogonal THz time-domain components via the conventional method as in Fig. 1, whereas Fig. 3(e) shows the spectral curve of a single THz time-domain pulse modulated by the Archimedean spiral tube, with the frequency interval of the spectral dips varying according to the input THz polarization azimuth angle. Here, to prevent the complete extinction of the PCA receiver on the linearly polarized THz wave, we set its extinction angle to be  $-22^\circ$ , different from all the incident THz polarization azimuth angles. This measurement style has been proved by us that it does not significantly affect the spectral SNR or alter the expected locations of the spectral dips (see supplementary material S2).

Subsequently, we substituted the average  $\Delta f$  from Fig. 3(e) in Eq. (1) to calculate the corresponding aperture  $D$ , and then, by using the following equation:

$$D(\theta') = r(\theta') + r(\theta' + 180), \quad (4)$$

we computed the corresponding  $\theta'$  and predicted the THz polarization azimuth angles ( $\theta = \theta' + 90$ ) to be  $2.6^\circ$ ,  $47.7^\circ$ ,  $88.3^\circ$ , and  $133.1^\circ$ , respectively, as plotted as circles in Fig. 3(f). It is evident that the THz polarization azimuth angles obtained by the two methods in Fig. 3(f) (bars vs circles) are essentially in agreement. This has been demonstrated that, compared to the conventional method (Fig. 1), our Archimedean spiral tube approach (Fig. 2) does not require any device manipulation (e.g., rotation, etc.), nor does it necessitate two separate measurements of the orthogonal THz polarization components. Instead, it can directly determine the linear polarization azimuth angle from the FT spectrum of a single THz time-domain pulse, thereby simplifying the measurement process and enhancing the detection efficiency.

In the above-mentioned experiments, four representative azimuth angles have been detected by the proposed CARR method. Furthermore, in the same manner, all  $180^\circ$ -azimuth angles can be retrieved if the THz PCA emitter is continuously rotated to make a broader range of THz polarization azimuth angles (from  $0^\circ$  to  $180^\circ$ ). Note that here the “rotate” refers to the rotation of the THz source (i.e., the used THz-PCA emitter or any other kinds) over the  $180^\circ$  range, not the rotation of our detection setup (the Archimedean spiral tube and the THz-PCA receiver). The recorded frequency-domain THz amplitude is depicted in Fig. 4(a), in which the resonance frequencies are marked with white dashed lines, and a continuous decrease in  $f_m$  with the increasing  $\theta$  can be observed. This phenomenon is as expected from the  $f_m$  formula that a larger  $D$  (corresponding to a larger  $\theta$  or  $\theta'$ ) leads to a smaller  $f_m$ . It is worth noting that here the extinction angle of the detection antenna was set at  $-10^\circ$



**FIG. 3.** (a)–(d) THz linear polarization states detected using the conventional method shown in Fig. 1 for polarization azimuth angles of 0°, 45°, 90°, and 135°. (e) THz spectra detected using the proposed CARR method as shown in Fig. 2(b) for the four polarization azimuth angles as depicted in (a)–(d). (f) Comparison of THz polarization azimuth angles obtained from (a)–(d) as bars and (e) as circles.

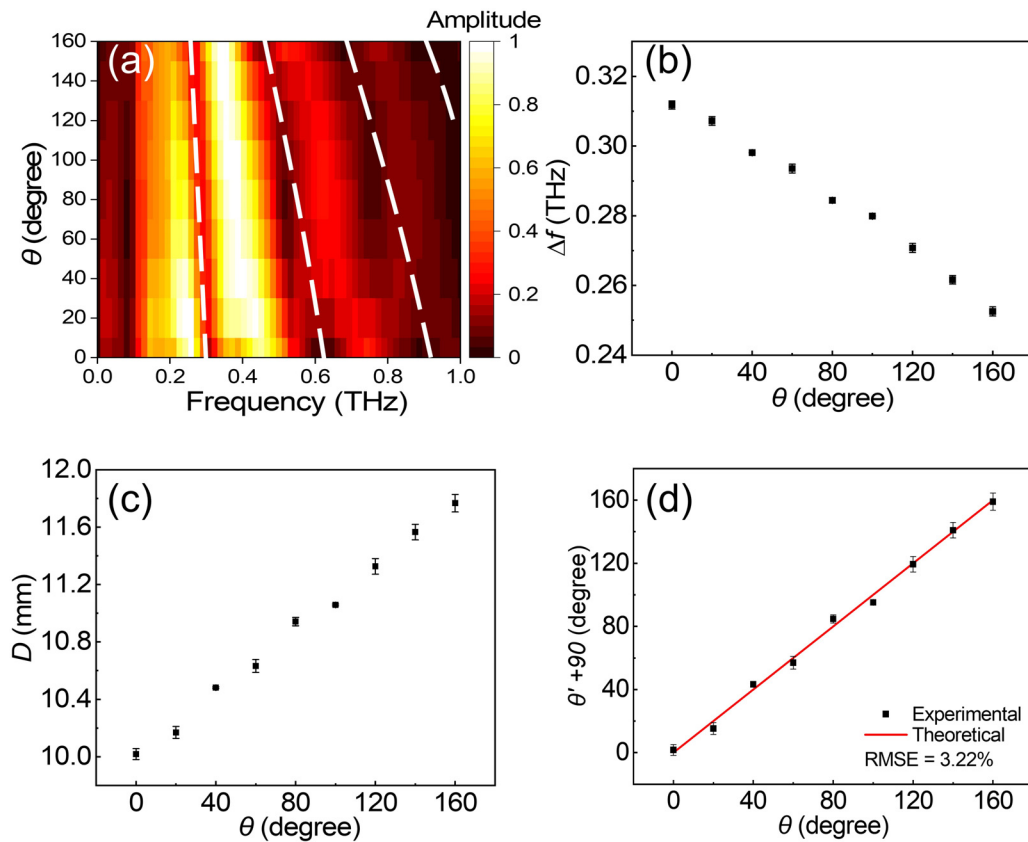
(i.e., 170°), and thus, the spectral results between  $\theta = 160^\circ$  and  $180^\circ$  have a low SNR, which are not shown in Fig. 4 (see also [supplementary material S2](#)).

Then, we performed a quantitative analysis by extracting the average interval between resonance frequencies ( $\Delta f$ ) at different  $\theta$  as shown in Fig. 4(b), which decreases from 0.31 THz at  $\theta = 0^\circ$  to 0.25 THz at  $\theta = 160^\circ$ . Based on this result and Eq. (1), the corresponding inner diameters  $D$  can be calculated as illustrated in Fig. 4(c). Subsequently, we calculated the angles ( $\theta'$ ) corresponding to these  $D$  values according to Eq. (4), and the resultant ( $\theta' + 90^\circ$ ) are indicated by the black squares in Fig. 4(d). Additionally, theoretical values are also depicted in the same figure as the red line. One can see a close agreement between the two results with the root mean square error (RMSE) of only 3.22%.

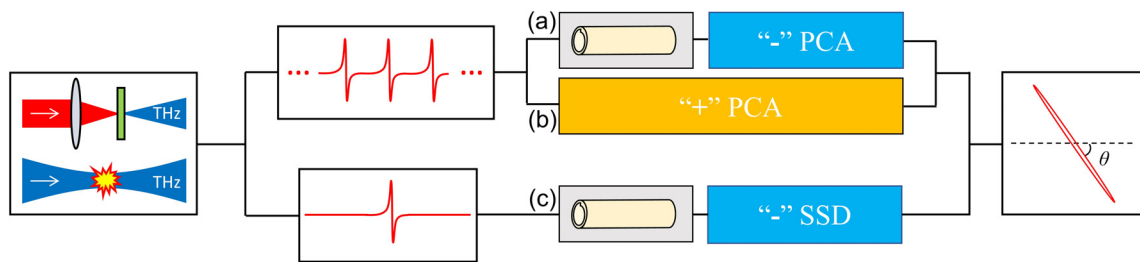
It is worth noting that, as can be seen from the experiments depicted in Figs. 3 and 4, in our scheme, the measured frequency requires a certain bandwidth, within which the polarization should also be approximately consistent. Therefore, in various application scenarios, one may need to first filter out the frequency band of interest as a pre-treatment before the proposed CARR measurements. Although this pre-treatment might increase the complexity of our method, it is also needed for traditional methods. Hence, our approach remains advanced because it does not require a rotation of the polarizer or detector or any other optical components. For a more detailed analysis of the above-mentioned content, please refer to

[supplementary material S3](#). Additionally, theoretically, our scheme can also detect the azimuth of elliptically polarized light, that is, the direction of the major axis of the polarization ellipse, which is further described in [supplementary material S4](#) for details.

On the other hand, our experiments above are mainly carried out in the manner of Fig. 5(a), where an Archimedean spiral tube and an ordinary THz PCA detector with a single metal slit (“–”) were employed. Compared with the THz PCA with orthogonal slits (“+”) in Fig. 5(b), which can simultaneously detect the orthogonal polarized THz components, our CARR method may not seem to offer a significant advancement, as both can measure the THz polarization azimuth angles without the need of device manipulations, such as rotation. However, our CARR method (and the Archimedean spiral tube) can also be combined with traditional THz single-shot detection (SSD) systems<sup>33</sup> (see [supplementary material S5](#)) as shown in Fig. 5(c), endowing them with polarization azimuth angle detection capabilities. This would enable a rapid diagnosis of the polarization angle at the level of single-shot and single-pulse during transient THz-optical processes, a feature that “+” THz PCAs lack as they currently operate exclusively in a multi-shot mode<sup>24,25,34</sup> (see [supplementary material S5](#)). In addition, the proposed Archimedean spiral tube in this work could also play potential roles in various applications like the tunable filter, the wavelength, and polarization multiplexer or the fast-scanning cavity, among others, as demonstrated in the [supplementary material S6](#).



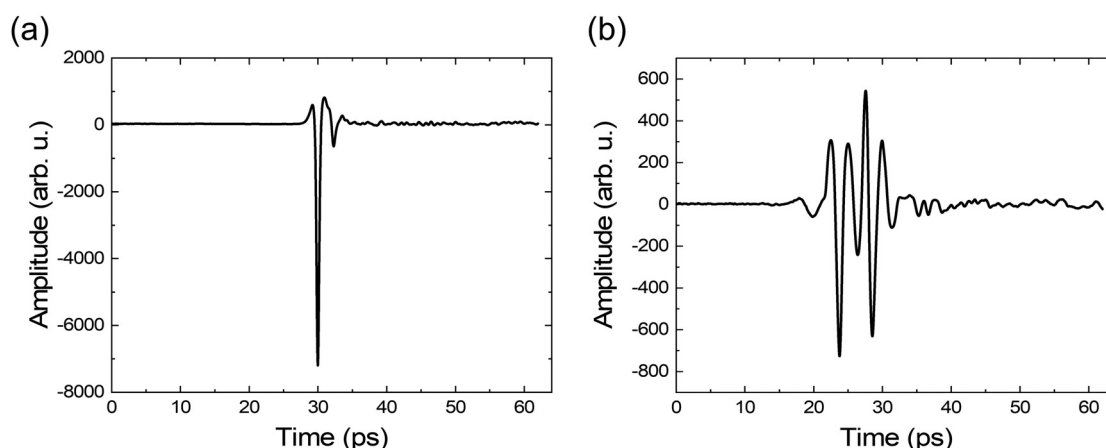
**FIG. 4.** (a) The output THz spectra from the Archimedean spiral tube with different input THz polarization azimuth angles ( $\theta$ ). (b) The average interval between resonance frequencies ( $\Delta f$ ) obtained from (a) as a function of  $\theta$ . (c) The calculated  $D$  based on (b) and Eq. (1). (d) The resolved polarization azimuth angle ( $\theta' + 90$ ) from  $D$  in (c).



**FIG. 5.** Comparison between (a) our method (Archimedean spiral tube) and (b) the THz PCA with orthogonal slits (“+”) for detecting the THz polarization azimuth angle. “—” means that the corresponding PCA or SSD (single-shot detection setup in (c)) does not have the ability of simultaneously detecting the orthogonal polarized THz components. The single- or multi-shot/pulse THz radiations could be from an intense-laser-induced THz source or a transient THz-matter interaction process, among others.

Moreover, it should be noted that our CARR cavity, although shaped like a waveguide, is indeed a THz modulation device. Because its primary purpose is not to transmit THz waves with low loss, but to encode the polarization azimuthal angle information into the THz time-domain waveform. Ultimately, the initial THz polarization azimuthal angle can be determined by the resonant frequencies (i.e., dip positions) on the output THz spectrum. Figure 6(a) presents the time-domain waveform of the THz emission from our PCA emitter. After passing through the CARR tube, the THz signal is

modulated with the output result as shown in Fig. 6(b). It can be seen from Fig. 6(b) that there is an attenuation of the THz energy. However, since this THz loss has no significant impact on the resonant frequencies or dip positions on the THz spectrum, this work did not provide a comprehensive study on this factor or other waveguide properties of the CARR tube. In short, our CARR cavity serves as a component of a “rapid linear polarization azimuth angle detector,” rather than being a conventional waveguide designed primarily for THz wave transmission.



**FIG. 6.** (a) The initial THz time-domain signal. (b) The THz time-domain signal after passing through a tubular CARR cavity with an aperture of  $D = 12$  mm. The Fourier-transformed spectra of (a) and (b) are shown in Fig. 2(c).

In summary, in this work, we have validated the use of CARR technique for rapid detection of linear polarization azimuth angles in the THz band. According to the CARR theory, changes in the inner diameter of the CARR tube lead to variations of the output resonant frequencies. Consequently, an Archimedean spiral tube with a gradually varying inner diameter was fabricated, which allowed us to build one-to-one connections between the three factors, namely, the resonant frequency, the inner diameter, and the azimuth angle of linearly polarized THz waves. By this method, we achieved the goal of encoding the spatial THz azimuth angle information into the THz spectrum (via a simple CARR tube), and the latter can be easily obtained from a single time-domain THz pulse waveform or even a single THz shot. Therefore, the proposed scheme not only significantly reduces the complexity of traditional methods, but also is expected to achieve real-time THz azimuth angle monitoring with high temporal resolution.

See the [supplementary material](#) for additional information.

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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Yangjun Mei:** Software (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yifu Tian:** Software (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yongpeng Han:** Investigation (equal); Software (equal); Writing – original draft (equal); Writing – review & editing (supporting). **Li Lao:** Resources (supporting); Writing – review & editing (equal).

**Jiayu Zhao:** Conceptualization (lead); Methodology (equal); Writing – original draft (lead); Writing – review & editing (lead).

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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