# Stable CW THz Spectroscopy with PLC-LN Hybrid Phase Modulator

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***Abstract*— We present a compact and stable continuous-wave terahertz spectroscopic system with a planar lightwave circuit-LiNbO$_3$ phase modulator for terahertz phase control. Thanks to significantly shortened optical paths with temperature control, the system enables fast vector measurement with effective phase stabilization. The phase stability of 2° was obtained over a period of 2 h.**

## I. INTRODUCTION

TERAHERTZ (THz) spectroscopy is attractive for non-destructive investigations of crystals, polymers, and biomaterials because of its transparency and special resolution [1,2]. Compared to time-domain spectroscopy, one potential advantage of a continuous-wave (CW) system is frequency selectivity with high and easily scalable spectral resolution simply with free-running CW lasers. The photo-mixing THz generation method is promising because it can support the widest frequency range for phase-sensitive spectroscopy and imaging by using homodyne detection [3–6]. Using electro-optic (EO) phase modulation without physically moving parts, such as a mechanical delay or chopper, fast THz phase control and vector detection is possible. However, in the homodyne detection scheme, environmental temperature ambiguity in the optical path induces sensitive phase variation, especially when a long-fiber setup is used [3]. Measurement stability is another important figure of merit in biomedical sensing with high absorption due to its weak signal. For phase-sensitive imaging, measurement stability limits the applicable imaging area. Therefore, we previously used silicon-photonic integration technology to shorten the optical path [7]. The integrated phase control circuit on Si-based planar lightwave circuits (PLCs) greatly enhances the phase stability of the system; however, the dynamic range degraded by amplitude noise due to the phase modulation mechanism in the Si PIN modulator.

In this paper, we present the implementation of a photo-mixing-based CW-THz vector spectroscopy system that uses silica-based PLC photonics for compactness and stability. By using the PLC-LiNbO$_3$ (LN) hybrid assembly technique [8], a photonic THz phase control circuit, composed of EO modulators, couplers, and waveguides, is hybrid integrated on a 400-mm$^2$-area of the silica-based PLC, which replaces the fiber-optic parts in the previously reported system [3, 5].

## II. MEASUREMENT

We experimentally demonstrated THz generation and vector measurement using an InGaAs-based photoconductive antenna (PCA), wideband uni-traveling photodiode (UTC-PD), and integrated phase control circuit with temperature control. Figure 1 shows a schematic diagram of the CW-THz homodyne spectroscopy system and photograph of an LN phase control photonic circuit integrated on the PLC platform. The PLC-LN hybrid assembly technique was originally developed for ultrafast optical communication frequency-shift-keying modulators [8]. In the THz phase control circuit, an LN waveguide is assembled with two PLCs in which 1 x 2 couplers, splitters, and a U-turned waveguide are formed. For THz wave generation, two individual lightwaves from a fixed-wavelength DFB laser diode (LD) and a tunable laser (TLS) are combined then photo-mixed in a UTC-PD [9]. The identical lightwaves are also delivered to a PCA for homodyne detection. The separated lightwave propagates through individual paths from the optical splitters after the Erbium-doped fiber amplifier (EDFA) to the optical couplers before the emitter and detector. To enhance stability, the proposed solution is to miniaturize the individual paths by photonic integration, especially in the critical section from the optical splitter to coupler. Therefore, LN components were used in the optical phase control and assembled in the section from the splitter to coupler with the PLCs, of which the total length is about 8 cm. The circuit was insulated in a box with a thermally controlled package with a Peltier module. Compared to a previous report, in which the total fiber length was about 40 cm [5], the setup size was significantly reduced by five times, resulting in a corresponding stabilization of the phase response. Furthermore, the thermally controlled package stabilized the temperature variation of the phase control circuit, by which the overall phase variation was comparable to the Si-PLC without thermal control [7].

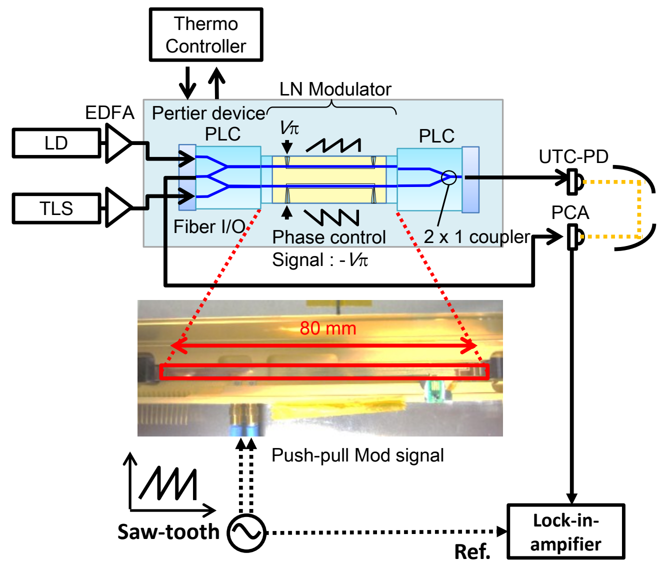


**Fig. 1.** Schematic diagram of CW-THz homodyne spectroscopy system and photograph of LN phase control photonic circuit integrated on PLC platform

For homodyne detection, using two saw-tooth driving voltages on two LN modulators, differential lightwave phase control enables fast and linear phase sweeps of THz waves.

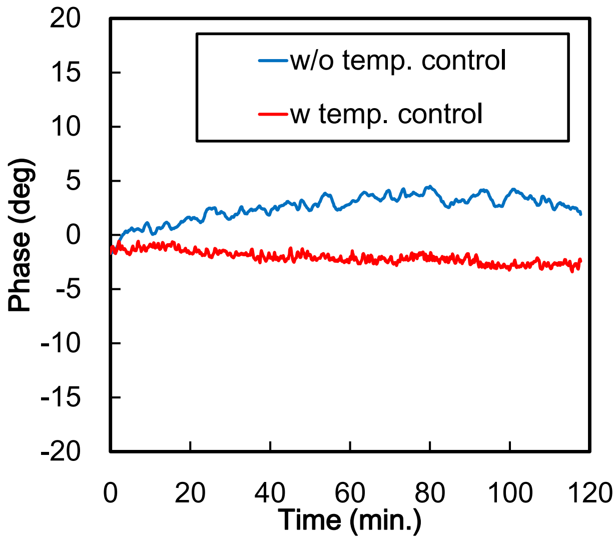


**Fig. 2.** Measured long-term variation of phase responses in 2 h with and without temperature control on phase control circuit

Furthermore, it suppresses the amplitude noise due to EO phase modulation in the detected signal [3]. The frequency response of the CW-THz homodyne system was measured from 0.2 to 2 THz with wavelength tuning of the TLS and synchronized lock-in detection. Using two off-axis parabolic mirrors, the path of THz waves contained about 30-cm-long free space in air between the emitter and detector. The integration time of the lock-in detection was 3 ms. To estimate the system's signal-noise-ratio, the noise level was measured with 1-s integration in the same frequency range without THz emission from the UTC-PD. The measured dynamic ranges were about 95 and 70 dB•Hz at 0.3 and 1 THz, respectively. These values are comparable to our previous report using a fiber setup [3]. Figure 2 shows the variation in the measured phase responses for 2 h in the open air of the experimental room. The phase response without temperature control on the phase control circuit clearly shows phase drifts due to temperature variation, which is 6° in 2 h. On the other hand, the phase stability with temperature control was less than ± 2° in 2 h, and the phase variation in the short term was only about 0.8°, which is comparable to that for a system using fiber-stretcher [10].

## III. CONCLUSION

We discussed a compact and stable photo-mixing-based CW-THz vector spectroscopy system that uses silica-based PLC photonics. By using the PLC-LN hybrid assembly technique, a photonic THz phase control circuit, composed of EO modulators, couplers, and waveguides, was hybrid integrated on the silica-based PLC. The experimental results show that the integrated photonic circuit with temperature control offers excellent phase stability and sufficient dynamic range. Therefore, combined with fast spectral measurement capability, the system is insensitive to the effect of environmental phase variation.

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