OCT technique for distance measurement using an RTD terahertz oscillator

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***Abstract*—We propose a method for distance measurement using terahertz waves based on the amplitude modulation of a resonant-tunneling-diode (RTD) oscillator and using a method similar to the optical coherence tomography (OCT). The terahertz output of the RTD oscillator is modulated in amplitude at a series of frequencies and sent to the target. The returning wave is demodulated and homodyne mixed with the original modulation signal at each of those frequencies. The distance to the target is calculated from the inverse Fourier transform of the series of mixer output signals. In principle, the distances to multiple targets can be measured simultaneously; here we report the experimental verification for the case of one and two targets.**

I. INTRODUCTION

TERAHERTZ (THz) waves, with a frequency range roughly from 0.1 to 10 THz, can be used to measure distances, which can be used in security and safety applications. In this report we describe a distance measurement principle based on the resonant-tunneling-diode (RTD) oscillator, which is a compact semiconductor device that we believe has a great potential as a practical THz-wave source.

Previously, we reported [1] the measurement of the absolute distance to a target using an RTD oscillator modulated at two frequencies, whereby we obtained a precision of 0.063 mm (standard deviation). However, by that method we can only measure one distance at a time. Here we propose a method that is based on a principle similar to that of the swept-source optical coherence tomography (OCT) technique and that allows the simultaneous measurement of multiple distances. We present our initial experimental findings.

II. METHOD AND EXPERIMENTAL SETUP

Figure 1 shows a schematic of the experimental setup. The sinusoidal output of a signal generator (SG), with a frequency of several GHz, is added to the bias voltage of the RTD oscillator (522 GHz carrier frequency) to generate an amplitude-modulated THz wave, which is sent to the reflecting target. The returning THz wave is demodulated by a Fermi-level managed barrier diode (FMBD) receiver [2]. Using an IQ mixer, two copies of the demodulated signal are mixed with two reference signals from the SG, one of which is 90° phase shifted by a hybrid coupler, and thus the two mixers produce a pair of quadrature (V_I, V_Q) signals, expressed by the following equations:

$$V_\mathrm{I}(f) = A\int_{-\infty}^{+\infty} R(z)\cos\left(2\pi f\cdot 2\frac{z}{c}\right)dz, \quad (1)$$

$$V_\mathrm{Q}(f) = A\int_{-\infty}^{+\infty} R(z)\sin\left(2\pi f\cdot 2\frac{z}{c}\right)dz, \quad (2)$$

where f is the modulation frequency, which in the ideal case is scanned continuously over an infinite range; c is the speed of light and A is an amplitude. The equations for V_I and V_Q also include the target reflectance distribution function $R(z)$, which accounts for the amount of reflected signal from each axial position z. In the simplest case, where the target is a single reflecting surface, $R(z)$ is equal to a delta function at the distance where this surface is positioned. The purpose of the radar is to determine the function $R(z)$.

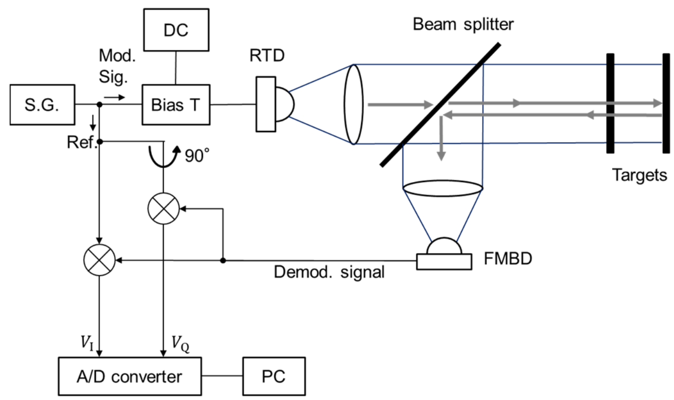

Fig. 1. Schematic of the experimental setup.

The two quadrature signals are measured at each modulation frequency. The distance measurement principle relies on this particular effect: when the modulation frequency is changed, the phase difference between the reference and the measurement signals will change, and the quadrature signals V_I and V_Q will vary sinusoidally, with a period depending on the propagation time difference between the reference and measurement paths. If that period is determined, the propagation time can be calculated, and hence the absolute distance to the target.

The reflectivity distribution function $R(z)$ can be obtained from Eqs. (1) and (2) by applying an inverse Fourier transform:

$$R(z) = \frac{2}{Ac}\int_{-\infty}^{+\infty}\left(V_\mathrm{I}(f) - iV_\mathrm{Q}(f)\right)\exp\left(i2\pi f\cdot 2\frac{z}{c}\right)df, \quad (3)$$

where i is the imaginary unit.

If the target consists of several reflecting surfaces placed at different distances, each of them will produce its own delta function in the calculated $R(z)$.

In practice, however, the modulation frequency can only have a limited number of discrete values. The infinite-range integral in Eq. (3) turns into a finite-range sum, and this has two consequences. First, the limited span of modulation frequencies will blur the calculated $R(z)$ and reduce the resolution of the distance measurement. Second, the discrete nature of the frequency adjustments will limit the distance measurement range. The two equations below give the distance resolution δz and the distance measurement range Δz.

$$\delta z = \frac{c}{2(f_{\max} - f_{\min})}, \quad (4)$$

$$\Delta z = \frac{c(N-1)}{2(f_{\max} - f_{\min})}, \quad (5)$$

where $f_{\min}$ and $f_{\max}$ are the minimum and the maximum modulation frequencies, respectively, and N is the number of frequency values, usually a power of 2. The distance resolution formula is the same as for the frequency-modulated continuous-wave (FMCW) radar.

III. RESULTS

To test the principle, we built the experimental setup shown in Figure 1 and placed a metallic mirror as the target on a motor stage, which we moved in 1 mm increments. At each position, the modulation frequency was adjusted from 3 to 18 GHz in 512 steps. The theoretical resolution δz is 10.0 mm.

The typical recorded signals for each stage position are shown in Figure 2, and their Fourier transform in Figure 3. When the motor stage is moved, the corresponding peak in the inverse Fourier transform moves as well, and the absolute distance calculated from the signals has a linear relationship with the relative position of the motor stage, as shown in Figure 4; as the deviations from the linear relationship are too small to see at this scale, the lower part of the figure is added to show the measurement errors, defined as the differences between the calculated distances and a linear fit of slope 1.

To increase the measurement precision, windowing is applied to the data before the Fourier transform, and a fitting routine is used to determine the peak position. With no windowing and with a three-point Gaussian peak fitting, the measurement error is 0.45 mm (standard deviation). When a Gaussian window of an optimized width is applied, the error reduces to 0.15 mm.

We have also started experimenting on simultaneously measuring two targets. We placed a half-mirror, made of a thin high-resistivity silicon plate, in the collimated beam and a metallic mirror behind it. Figure 5 shows an example of the data obtained under the same conditions as when measuring the distance to a single target: the higher peak and the lower peak correspond to the half-mirror and the full mirror, respectively. It is to be expected that when the distance between the two targets is smaller than the resolution, the two peaks will overlap partially and make distance measurements difficult.

IV. CONCLUSION

We proposed a terahertz-wave distance measurement method using an RTD oscillator, based on an OCT method. With a single reflecting surface, a measurement precision of 0.15 mm was obtained. We verified that the simultaneous distance measurement of two targets is also possible.

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REFERENCES

[1] A. Dobroiu, R. Wakasugi, Y. Shirakawa, S. Suzuki, and M. Asada, *Photonics* 2018, 5, 52.

[2] H. Ito and T. Ishibashi, *Electron. Lett.*, vol. 54, pp. 1080–1082, 2018.

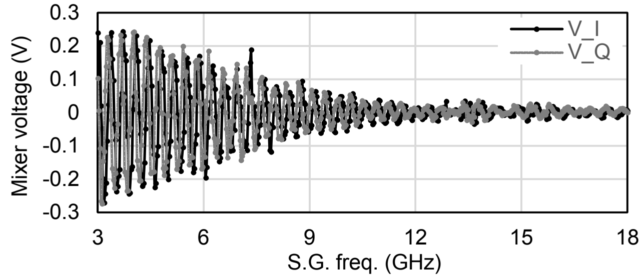

Fig. 2. Signals measured on a single target. The modulation frequency was adjusted from 3 to 18 GHz in 512 steps. The amplitude decrease with frequency is caused mainly by an inherent low-pass filter in the RTD oscillator.

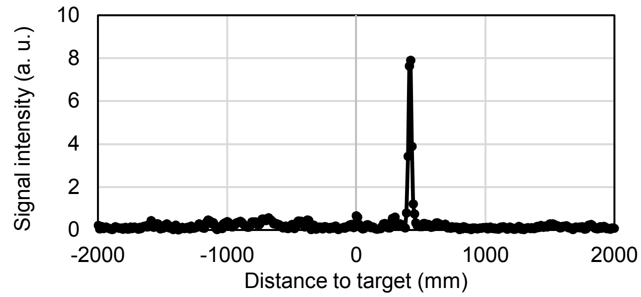

Fig. 3. The result of the inverse Fourier transform of the signals in Fig. 2. The peak near 400 mm shows the absolute distance to the target.

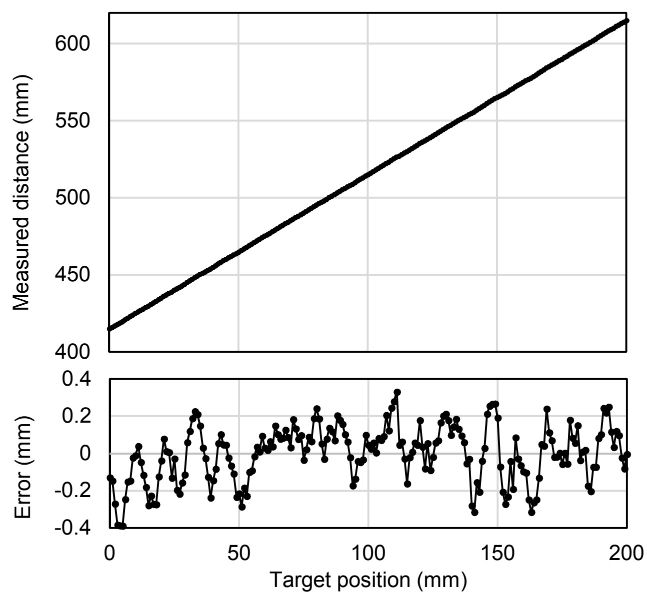

Fig. 4. The measured absolute distance for a single target. A Gaussian window is applied and the peak position is found by a three-point Gaussian. The standard deviation is found to be 0.15 mm.

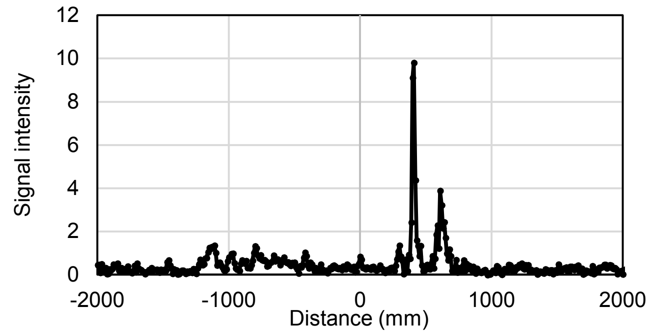

Fig. 5. Distance measurement result on two targets. The two peaks at about 400 mm and 600 mm correspond to the half-mirror and the full mirror, respectively.