Distance measurement using a subcarrier frequency-modulated continuous-wave radar based on a resonant-tunneling-diode oscillator

Adrian Dobroiu[1], Yusuke Shirakawa[1], Safumi Suzuki[1], Masahiro Asada[1], Hiroshi Ito[2]
[1]Tokyo Institute of Technology, Tokyo, 152-8552 Japan
[2]Kitasato University, Kanagawa, 252-0373 Japan

***Abstract*—We have previously introduced a new principle for distance measurement using terahertz waves, similar to the frequency-modulated continuous-wave (FMCW) radar, but where the sawtooth frequency modulation is applied to an amplitude modulation subcarrier of the terahertz wave instead of the carrier itself. The method is particularly useful when the terahertz-wave source is a resonant-tunneling-diode (RTD) oscillator, which can be more reliably modulated in amplitude than in frequency. This report describes using the new principle in a typical radar configuration as well as ways of achieving a better accuracy.**

I. INTRODUCTION

TERAHERTZ electromagnetic waves are expected to find applications in product inspection, safety and homeland security scenarios, such as vehicle anti-collision systems and body scanners, where distance measurement is often necessary. Several techniques are available for distance measurement using terahertz waves, but many of them use complex, expensive, large, heavy, and energy-intensive devices, hardly suitable for real-world applications. A good candidate to solve the requirements for a practical terahertz-wave source is the resonant-tunneling-diode (RTD) oscillator, a solid-state, room-temperature, compact device that generates continuous terahertz-wave outputs up to almost 1 mW and at frequencies up to 2 THz and, importantly, can be very easily modulated in amplitude.

We recently introduced [1] the subcarrier frequency-modulated continuous-wave (FMCW) distance measurement principle. At that time, the source and the detector were placed in front of each other and their mutual distance was varied for the experimental verification. Here we report the performance of the new method when the optical setup is given the typical radar configuration and when two targets are measured simultaneously. Additionally, we report the results of several techniques that we tested in an attempt to improve the measurement precision.

II. PRINCIPLE

The principle of the FMCW radar is shown in Figure 1. In our case, the carrier frequency remains unchanged, while the frequency of the amplitude-modulated subcarrier is swept linearly and repeatedly between $f_{\min}$ and $f_{\max}$ as given by

$$f(t) = f_{\min} + (f_{\max} - f_{\min})\frac{t}{T}, \tag{1}$$

where t is time and T is the repetition period. The wave returning from the target has the same frequency profile, but arrives at a different time and has a different instantaneous frequency. When the received signal and the transmitted signal are mixed, the resulting beat has the following frequency:

$$f_{\mathrm{IF}} = (f_{\max} - f_{\min})\frac{t_{\mathrm{meas}} - t_{\mathrm{ref}}}{T}, \tag{2}$$

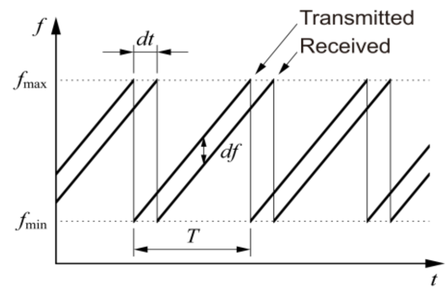

Fig. 1. Principle of the FMCW radar in the case of one reflecting target.

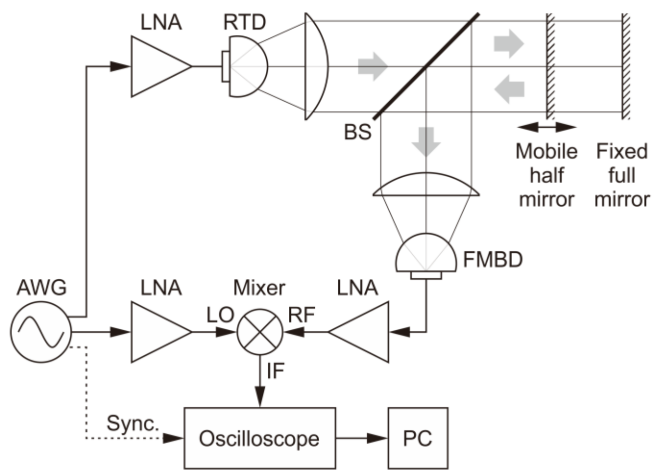

Fig. 2. Schematic of the experimental setup for the particular case of using two targets. LNA: low-noise amplifier; BS: beamsplitter. Auxiliary parts (bias tees, power supplies, etc.) are not shown.

where t_{meas} and t_{ref} are the propagation times between the signal generator and the mixer on the measurement path (through the optical setup) and the reference path, respectively.

The beat frequency f_{IF} can be determined by digitizing and recording the beat signal, calculating its Fourier transform, and finding the peak position. Then the distance to the target can be calculated:

$$d_{\mathrm{target}} = \frac{T}{f_{\max} - f_{\min}} f_{\mathrm{IF}} \frac{c}{2\, n_{\mathrm{air}}}, \tag{3}$$

where c is the speed of light in vacuum and n_{air} is the refractive index of air, about 1.0003 at terahertz frequencies.

When the target consists of parts placed at various distances, each of them will produce its own peak in the Fourier transform. The radar's ability to resolve these peaks and discriminate targets that are close to each other axially is given by the depth resolution:

$$\delta d_{\mathrm{target}} = \frac{1}{f_{\max} - f_{\min}} \frac{c}{2\, n_{\mathrm{air}}}. \tag{4}$$

This formula shows that the only way to improve the resolution is by using a wider frequency sweep. It is important to note, however, that the resolution is not the same as the distance measurement error; the latter can be much smaller.

III. Experimental verification

To verify the distance measurement principle experimentally in the terahertz-wave range, we built the setup shown in Figure 2. The terahertz-wave source is an RTD oscillator emitting about 10 µW of power at 511 GHz when simply biased with a DC voltage. The emitted terahertz wave is modulated in amplitude just by adding the output of an arbitrary waveform generator (AWG) to the RTD bias voltage. The AWG is set to produce a linear frequency sweep from 3.5 to 10.5 GHz with a period of about 4 µs.

The terahertz wave propagates as a collimated beam to the target (the two mirrors in Figure 2) and back to the detector, which is a Fermi-level managed barrier diode (FMBD) [2]. After demodulation, only the subcarrier remains. This is sent to the RF input of a mixer, while the LO input is fed with a copy of the swept frequency signal used for the RTD modulation. The IF signal is recorded by an oscilloscope, which also performs the Fourier transform. The result is transferred to a computer that detects the peak(s) in the Fourier transform and calculates the distance(s). The same computer controls the motor stage.

After our report in [1], in addition to configuring the optical setup to work in the typical optical configuration of a radar system, we have implemented several improvements in the signal processing and in the experimental setup. For instance, we applied the background subtraction technique to remove systematic peaks—which we call ghosts—in the Fourier transform, caused by signal reflections inside cables and in the optical setup; the method consists in recording and then subtracting the Fourier transform obtained without the targets. For the same purpose, we also adjusted the length of cables such that the peaks we need to measure fall in a region where these ghosts are weaker. The frequency band of the FMCW was additionally extended from 3 GHz to 7 GHz, which reduced the peak width to less than half and thus improved the resolution.

With these improvements, we were able to measure the distance to a single target with an error of 0.36 mm (standard deviation), as shown in Figure 3. When we used two targets, the errors were 0.61 mm for the half mirror and 1.1 mm for the full mirror, as shown in Figure 4. The theoretical resolution of the radar, calculated from Equation (4), is about 21 mm.

Conclusions

We presented results on the experimental verification of a newly proposed radar principle, based on the FMCW technique, allowing absolute distances to be measured simultaneously.

This work was supported by JSPS grant-in-aid (16H06292), JST-ACCEL (JPMJMI17F2), and JST-CREST(JPMJCR1534).

References

[1] Y. Shirakawa, A. Dobroiu, S. Suzuki, M. Asada, and H. Ito, "Principle of a Subcarrier Frequency-modulated Continuous-wave Radar in the Terahertz Band Using a Resonant-tunneling-diode Oscillator," *2019 44th Int. Conf. IRMMW-THz*, Paris, France, 2019, 4658605.

[2] H. Ito and T. Ishibashi, "Low-noise heterodyne detection of terahertz-waves at room temperature using zero-biased Fermi-level managed barrier diode," *Electron. Lett.*, vol. 54, pp. 1080–1082, 2018.

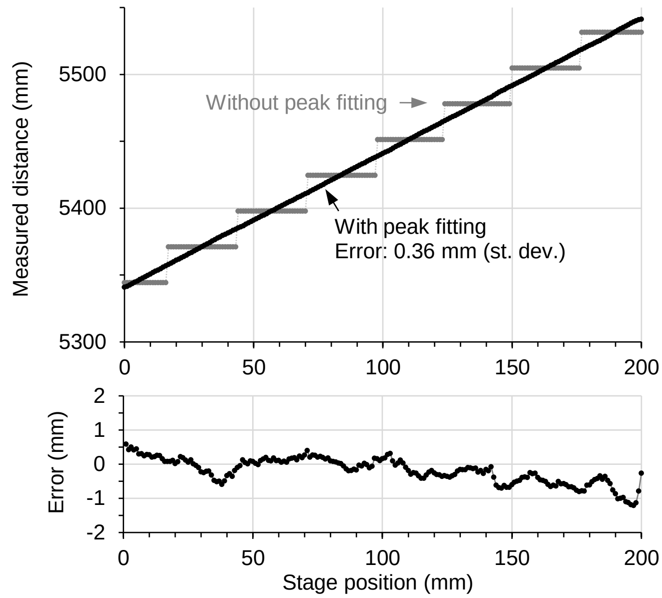

Fig. 3. Measurement on a single target with a frequency sweep from 3.5 to 10.5 GHz. Top graph: absolute distance measured by the radar vs the relative position of the motor stage. The result without peak fitting is shown for reference. Bottom graph: the measurement error, defined as the difference between the data and a linear fit of slope 1.

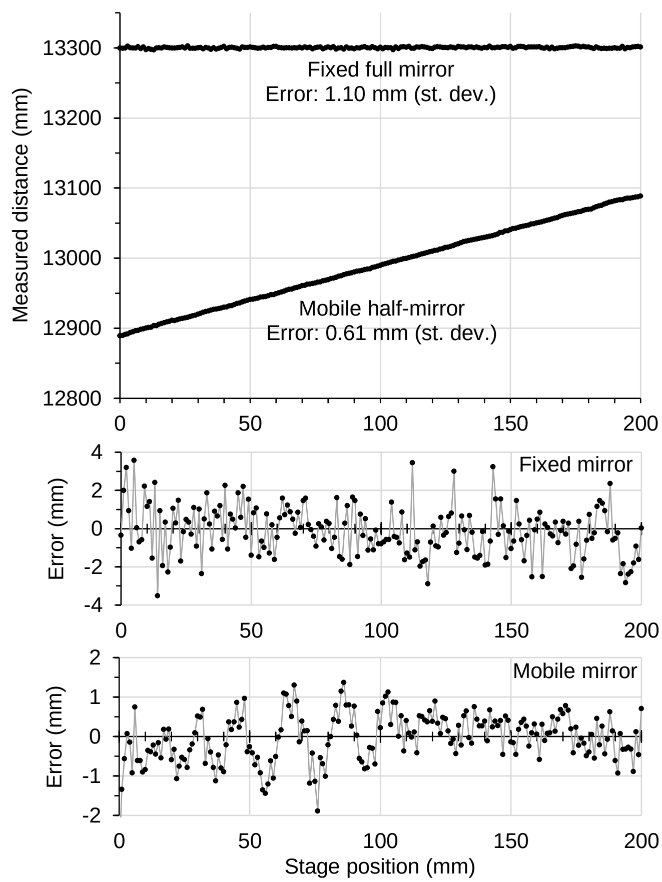

Fig. 4. Radar measurement result on a double target, consisting of a mobile half-mirror and a fixed full mirror. The mobile mirror was moved in 1 mm increments. The top graph shows the absolute distance to the target as measured by the radar, whereas the two bottom graphs show the measurement error, obtained as the difference between the measured data and a linear fit with slopes 0 and 1 for the fixed and mobile mirrors, respectively. The measurement was done using a frequency sweep from 3.5 to 10.5 GHz.