A simple-structure FMCW radar test system using PLL-Gunn oscillator and fundamental mixer in 79 GHz band

Kohei Fujiwara and Hidehiko Yamaoka
Tokyo Metropolitan Industrial Technology Research Institute
2-4-10, Aomi, Koto-ku, Tokyo 135-0064, Japan
Email: fujiwara.kohei@iri-tokyo.jp, yamaoka.hidehiko@iri-tokyo.jp

Tatsunori Onzuka and Shingo Ozaki
NIHON DEMPA KOGYO CO., LTD.
1-47-1, Sasazuka, Shibuya-ku, Tokyo 151-8569, Japan
Email: onzuka@ndk.com, ozaki.shingo@ndk.com

Yoneo Akita and Yoshikazu Fujinaka
Mebius Corporation
2-10-27, Kitasaiwai, Nishi-ku, Yokohama-city, Kanagawa 220-0004, Japan
Email: y_akita@mebius.co.jp, y_fujinaka@mebius.co.jp

***Abstract*—In this study, a simple frequency-modulated continuous wave (FMCW) radar test system for an anti-collision automobile radar in the 79 GHz band has been developed. This system consists of a down-converter based on a fundamental mixer with a phase-locked loop-Gunn oscillator and a mixed domain oscilloscope or a digital oscilloscope. This system can evaluate an FMCW signal in the time domain, which includes the evaluation of the chirp rate, chirp width, chirp length, and linearity. By employing the Gunn oscillator, the down-converter attains a very simple configuration. The down-converter has a conversion gain of 7.8 dB at 79 GHz in typical conditions and a bandwidth of 4 GHz. In this study, we explain the development of the radar test system and demonstrate the same using an FMCW chipset evaluation board.**

Keywords*—*E-band; FMCW radar; Gunn oscillator

I. Introduction

Recently, automatically controlled vehicles are being actively developed by many companies worldwide. To realize such vehicles, active safety technologies, such as pre-crash safety (PCS) systems and adaptive cruise control (ACC) systems, are strongly required [1]. The PCS system can minimize the crash damage on detecting an imminent collision. The ACC system maintains a safe distance between vehicles. There are many sensing equipment for similar purposes. For example, laser, camera, and ultrasonic methods have already been implemented in currently selling vehicles. However, even though such sensing systems can be easily and inexpensively implemented in vehicles, the performance of these methods strongly depends on the weather environment.

Although a radio wave is attenuated in rain, the radar systems are still functional. Therefore, it has become a trend to employ a frequency-modulated continuous wave (FMCW) radar in a millimeter-wave band for the PCS and ACC systems. The FMCW radar transmits a sweeping radio wave of several tens of mW to a moving object and detects the reflected wave to measure its position and velocity as well as its distance from another object. Thus, an FMCW radar system has the advantage of having lower transmitting power and cost than a traditional pulse radar system.

The FMCW radar for an automobile is allocated both 77 GHz and 79 GHz bands, and their maximum allowed bandwidths are 1 GHz and 4 GHz, respectively. Especially, in the 79 GHz band with a usable bandwidth of 4 GHz, the radar can detect an object of approximately 4 cm size. It does that using a high-speed frequency sweep; for example, the velocity resolution is improved by 1.9 m/s in a 1 ms sweep time. Thus, the radar can differentiate a pedestrian from a vehicle. To realize these performances, it is important to maintain frequency linearity and signal purity in the radar system, because degradations in these parameters reduce the accuracy and resolution of range and velocity of the radar system.

Consequently, the FMCW signal characteristics should be measured in the time-domain. However, in general, it is difficult to measure the FMCW chirp rate, chirp length, chirp width, and linearity in the time-domain using a conventional spectrum analyzer. Therefore, it is necessary to prepare a time-domain FMCW test system, which is cost-effective and easy to handle. In this study, we explain and verify the performance of the proposed 79 GHz band FMCW radar test system based on a down-converter implemented by a phase-locked loop (PLL)-Gunn oscillator and a fundamental mixer with a time-domain measuring instrument.

II. Test System

A. FMCW Signal Measurement

Fig. 1(a) shows an ideal linear FMCW radar signal with the up-chirp slope. A voltage-controlled oscillator (VCO) or a PLL synthesizer is employed for a linear sweeper. The transmitted and received signals are described by the solid and dotted lines, respectively. The frequency modulated signal has a specific bandwidth of f_{sweep}, chirp length of t_{cl}, and chirp rate. The beat frequency f_B is measured by a frequency shift caused by the reflected signal from a target. The beat frequency is proportional to the round-trip time t_p. Both the range and the radial velocity are obtained by the measured frequency shift f_B.

If the transmitted signal has non-linearity, as shown in Fig. 1(b), which is caused by a change of ambient environment in the VCO or PLL synthesizer, the beat frequency by a fast Fourier transformation (FFT) of a target will not be constant. This effect decreases the range, resolution, and radial velocity accuracy. Fig. 1(c) shows an effect of rippling, which causes the undesired side-lobes in the IF spectrum. This effect too decreases the above accuracy and resolution. Thus, the linearity of the linear frequency sweeper is the corner stone of the radar system. Consequently, in FMCW signal measurement, it is important to measure the chirp width, chirp length, chirp rate, and linearity.

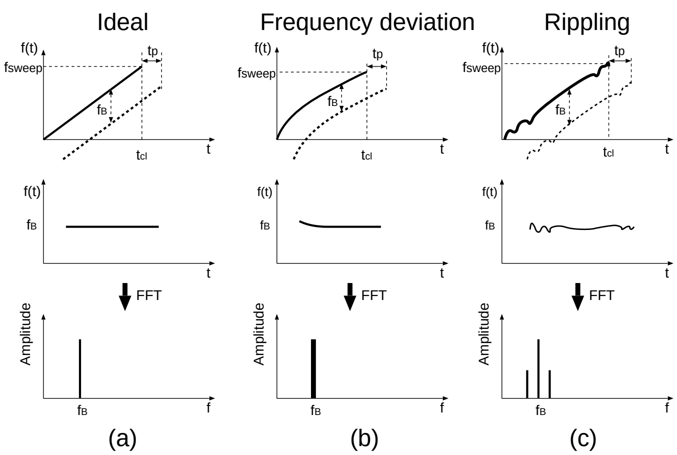

Fig. 1. (a) Ideal linear FMCW radar signal, (b) frequency deviation by non-linearity, and (c) rippling.

B. Configuration and Requirements

The FMCW radar test system consists of a down-converter and a conventional digital oscilloscope or a mixed domain oscilloscope, as shown in Fig. 2. The down-converter frequency-converts from a FMCW signal in 79 GHz band to that in a microwave-band to observe the chirp width, chirp rate, chirp length, and linearity in the time-domain with these measuring instruments. Using the mixed domain oscilloscope, the time-domain characteristics can be directly obtained by a function of the real-time spectrum analyzer with the maximum bandwidth of 6 GHz inside the oscilloscope [2]. Employing this advantageous function makes it possible to configure an affordable simple-structure test system. However, the mixed domain oscilloscope has three bands of a block down-converter [3]. Therefore, the IF frequency must be injected to the mixed domain oscilloscope within the bands while measuring the FMCW signal. Another method is to analyze the time-domain data from a digital oscilloscope by the quadrature-demodulation method in the dedicated software by Mebius Corporation.

The requirements of the 79 GHz FMCW radar test system are summarized in Table I. An RF input frequency from the 77 GHz–81 GHz band and a local oscillation (LO) frequency of 76.3 GHz are chosen. The required down-conversion gain is higher than 6 dB at the center frequency of 79 GHz. The input 1 dB compression point (P1dB) is more than 0 dBm. The overall noise figure is less than 16 dB. The LO frequency accuracy is within 0.5 ppm. The adaptive measuring instruments are both, a conventional digital oscilloscope with

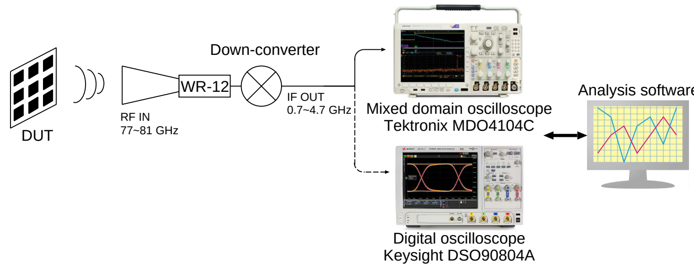

Fig. 2. Configuration of the 79 GHz band FMCW radar test system.

the analog bandwidth of more than 6 GHz and a mixed domain oscilloscope. Further, the IF frequency should be a few GHz for the signal. The swept frequency information in the time-domain can be directly displayed by the mixed domain oscilloscope [2]. Therefore, the chirp rate, chirp length, chirp width, and linearity parameters are evaluated easily.

TABLE I. SYSTEM REQUIREMENTS OF THE 79 GHZ TEST SYSTEM.

RF input frequency	77 GHz–81 GHz
Local frequency	76.3 GHz
IF frequency	0.7 GHz–4.7 GHz
Typical conversion gain	>6 dB
Input P1dB	>0 dBm
Noise figure	<16 dB
LO Accuracy	<0.5 ppm @25°C
Adaptive measuring instruments	Digital oscilloscope (BW>6 GHz) and mixed domain oscilloscope
Measurement addendums	Chirp rate, chirp length, chirp width, and linearity

III. 79 GHZ DOWN-CONVERTER

The 79 GHz down-converter is an essential component required to down-convert from a millimeter-wave signal to a few GHz to analyze on an oscilloscope. We developed the converter by combining it with a Gunn oscillator and a fundamental mixer. The PLL-Gunn oscillator was designed and implemented by NIHON DEMPA KOGYO CO., LTD., Tokyo, Japan. The developed oscillator contributes a simple circuit configuration and is easy to setup and operate.

A. Down-Converter Configuration

The 79 GHz fundamental mixer is designed based on the V-band fundamental mixer for the IEEE802.11ad test system [4]. The block diagram of the 79 GHz band down-converter is shown in Fig. 3. A bias voltage of 1.28 V is applied to this mixer to improve the efficiency of frequency-conversion. The 79 GHz mixer consists of a single balanced mixer with a rat-race-circuit and a Schottky-barrier diode; a low pass filter (LPF) with a DC block capacitor; a DC cut circuit; and a broadband WR-12 waveguide-to-microstrip line transducer [5]. The cutoff frequency of the LPF is designed to be 7 GHz. All parts are mounted on a polytetrafluoroethylene printed circuit board. The PLL-Gunn oscillator is used for the LO oscillator to be simple-structured and cost-effective. The down-converted signal is pre-amplified by a broadband amplifier of the typical gain of 26 dB to obtain enough signal level.

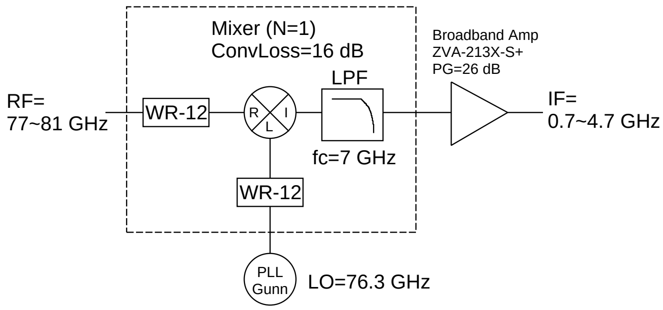

Fig. 3. Block diagram of the 79 GHz band down-converter.

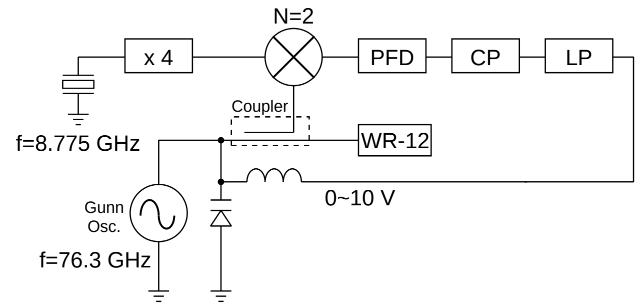

Fig. 4. Block diagram of PLL-Gunn oscillator.

B. PLL-Gunn Oscillator

In general, a Gunn oscillator is employed as a reliable, compact, and low-cost solid-state millimeter-wave source. It exhibits various desirable characteristics, such as high power, low phase noise, and 1/f noise. However, using a general Gunn oscillator is difficult to adjust an oscillation frequency and to maintain frequency stability because of the free-running oscillation mechanism. Thus, it has an individual difference in frequency and output power.

To employ the LO for the down-converter with frequency stability, a PLL-Gunn oscillator has been developed. It is based on the free-running oscillator with a varactor diode for frequency tuning. The free-running Gunn oscillator is fabricated on an aluminum nitride substrate using a flip-chip Gunn diode. This technology can realize a low-cost mass production owing to the use of unpackaged flip-chip Gunn diodes and flip-chip bonding technology. It has a high output power of more than 20 mW in the W-band.

The block diagram of the PLL-Gunn oscillator is shown in Fig. 4 and the photograph of the PLL-Gunn oscillator is shown in Fig. 5. A reference signal of 35.1 GHz is generated by multiplying the frequency four times. The frequency standard used is the 8.775 GHz temperature-controlled crystal oscillator (TCXO). The standard signal is frequency-mixed in a second order harmonic mixer with a signal of 76.3 GHz, which is generated by a free-running Gunn oscillator via a directional coupler. Further, the frequency-converted signal of 6.1 GHz is injected into a phase frequency detector (PFD), a charge pump (CP), and a loop filter (LP) to change a frequency difference to a voltage difference between 0–10 V. The voltage from the PFD is applied to a varactor diode to fine-tune the desired oscillation frequency. A signal is produced by the WR-12 waveguide, which is prepared on the bottom of the module. More than 10 dBm output is obtained at the bias voltage of 3.7 V. The frequency accuracy is 0.13 ppm. Fig. 6 shows the phase noise characteristics of the packaged PLL-Gunn oscillator by changing the frequency offset from 100 Hz to 10 MHz using the Rohde & Schwarz FSW67 spectrum and signal analyzer with the FSZ-110 W-band down-converter and the phase noise measurement option FSW-K40. As a result, the phase noise at the offset of 1 kHz is −53.3 dBc/Hz.

C. Performance

The down-conversion gain with a sweep of the RF is shown in Fig. 7. The injected LO signal level from the PLL-Gunn oscillator is 11.7 dBm; moreover, the RF sweep range is 79.0

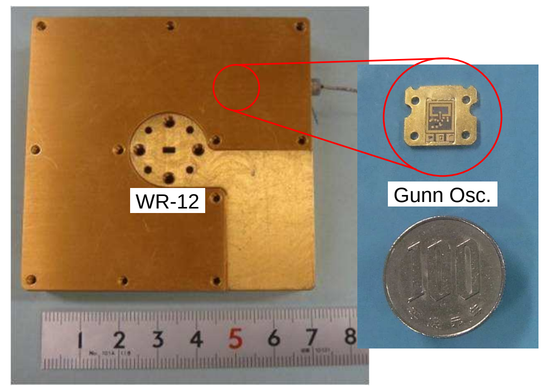

Fig. 5. Photograph of PLL-Gunn oscillator.

± 2.0 GHz. The performance is satisfactory owing to a typical conversion gain of 6 dB. The measured noise figure is 14.8 dB at the center frequency of 79 GHz. The P1dB is taken using a Keysight S10MS-AG millimeter-wave source module and the Rohde & Schwarz FSW67 spectrum and signal analyzer. Fig. 8 shows the linearity characteristics for the down-converter by sweeping the input power from −37.0 dBm–8.0 dBm at the frequency of 79 GHz. The linearity is kept with the input power between −37.0 dBm–8.0 dBm. Fig. 8 shows the photograph of the internal structure of the 79 GHz band down-converter. A typical IF spectrum response by the down-conversion is measured as shown in Fig. 9. The spectrum is produced by

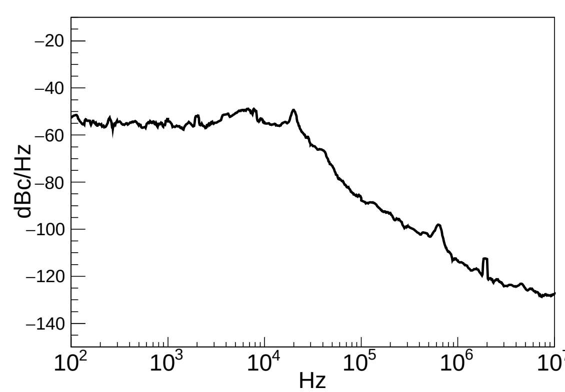

Fig. 6. Phase noise characteristics of the PLL-Gunn oscillator by changing the frequency offset from 100 Hz to 10 MHz.

injecting an RF signal of 77 GHz continuous wave. The second order harmonic of 53.6 dBc is obtained at the frequency of 1.4 GHz.

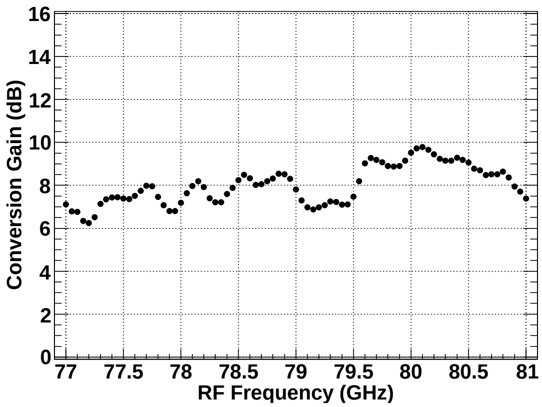

Fig. 7. Down-conversion gain by sweeping the RF frequency from 77 GHz–81 GHz at 76.3 GHz LO frequency with a power of 11.7 dBm from the PLL-Gunn oscillator.

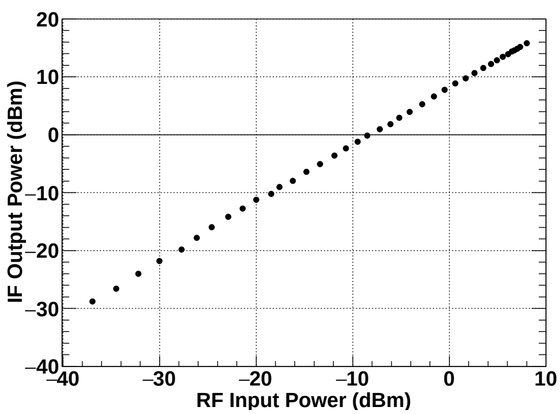

Fig. 8. Measured output IF power and input RF power by sweeping RF power from −37.0 dBm–8 dBm at input frequency of 79 GHz.

IV. System Evaluation

The performance evaluation of the test system is conducted using an evaluation board of a millimeter-wave sensing device in an anechoic chamber. The emitted FMCW signal is received and down-converted by the down-converter using a horn antenna with the typical gain of 25 dBi. The down-converted signal is transmitted from input into the real-time spectrum analyzer on the MDO4104C mixed domain oscilloscope or the Keysight DSO90804A digital oscilloscope to obtain the chirp rate, chirp length, chirp width, and linearity. The DSO90804A has an analog bandwidth of 8 GHz. These figures are obtained using a signal analysis software developed by Mebius Corporation and a Keysight vector signal analyzer (VSA), 89600 v20.0, with the 89601B/BN-BHP FMCW option [6]. The evaluation board is used as a transmitter, which is the AWR1443BOOST evaluation module from Texas Instruments Incorporated [4]. This sensing device has the ability of producing an output power of 10 dBm and a maximum antenna gain of 12 dBi using

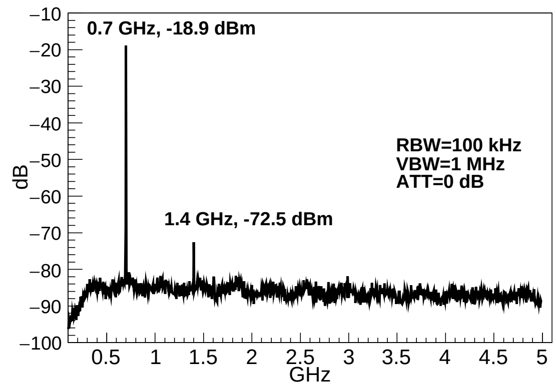

Fig. 9. IF spurious response by down-conversion.

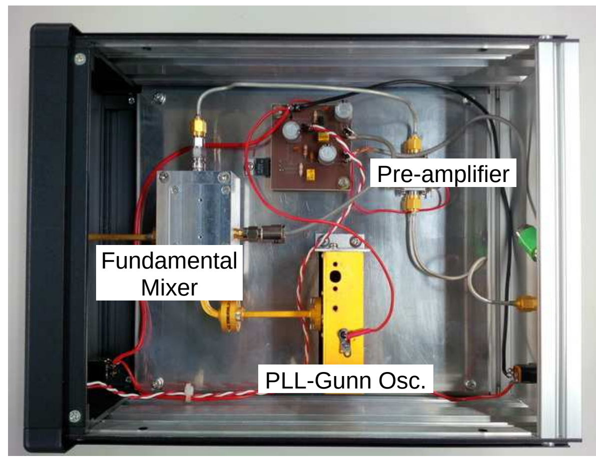

Fig. 10. Photograph of the internal structure of the 79 GHz band down-converter.

printed antennas. The measured equivalent isotopic radiated power (EIRP) is 18.9 dBm-EIRP at the frequency of 80.5 GHz. The evaluation board generates a saw-tooth waveform with time delay. According to the constraint of the input frequency range over the real-time spectrum analyzer on the mixed domain oscilloscope [3], a transmitting signal is configured by the chirp width of 1000 MHz at the center frequency of 80.5 GHz, the chirp length of 200 μs, the chirp rate of 5 MHz/μs, and the time delay of 10 μs. As per this configuration, the IF frequency is between 3.7 GHz and 4.7 GHz.

The distance and the height of both the transmitter and the down-converter are 1.65 m and 1.54 m, respectively. Thus, the estimated transmission loss by Friis's equation is 74.9 dB at 80.5 GHz, and the estimated receiving power is −56 dBm. Fig. 11 shows the experimental setup in an anechoic chamber.

V. Evaluation Results

The down-converted signal is analyzed using a digital oscilloscope with two types of signal analysis software, which are Keysight VSA v20.0 and the software by Mebius Corporation, or the real-time spectrum analyzer on a mixed domain oscilloscope. The performance comparison of each measurement method is summarized in Table II. The chirp

TABLE II. SYSTEM REQUIREMENTS OF THE 79 GHZ TEST SYSTEM.

	Configured value	VSA v20.0+DSO90804A	Mebius+DSO90804A	MDO4104C
Chirp width	1000 MHz	969.0 MHz	985.4 MHz	992.0 MHz
Chrip length	200 μs	194.9 μs	198.3 μs	198.5 μs
Chirp rate	5 MHz/μs	4.97 MHz/μs	4.97 MHz/μs	5.00 MHz/μs
Linearity	N/A	115 kHz/μs	127 kHz/μs	799 kHz/μs

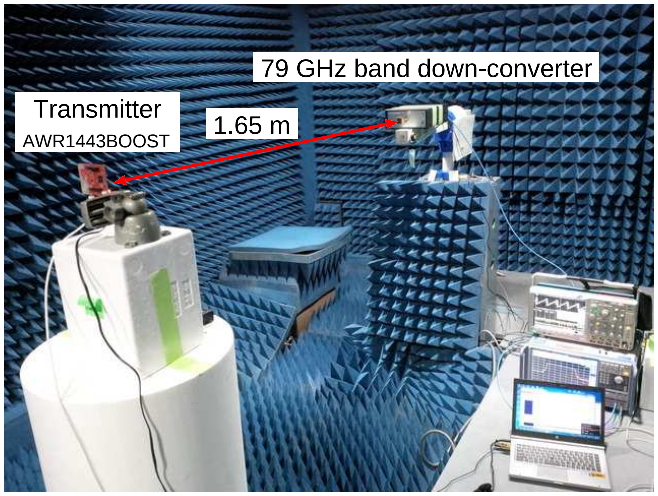

Fig. 11. Experimental setup in an anechoic chamber.

rate results are comparable to each other. The measured chirp width is obtained as 988.1 MHz by the Rohde & Schwarz FSW67 spectrum analyzer with the FSZ-110 W-band down-converter. The chirp width and length analyzed by the VSA v20.0 is smaller than the other results. It might be caused by the difference of the analyzing algorithm in the VSA software. The linearity obtained by the MDO4140C mixed domain oscilloscope is approximately six times larger than the other results. This might also be the reason of why there is a difference in the analyzing algorithm in the MDO4140C mixed domain oscilloscope. Fig. 12 shows the measured and quadrature-demodulated FMCW radar signal from the down-converter using the DSO90804A oscilloscope with the software by Mebius Corporation.

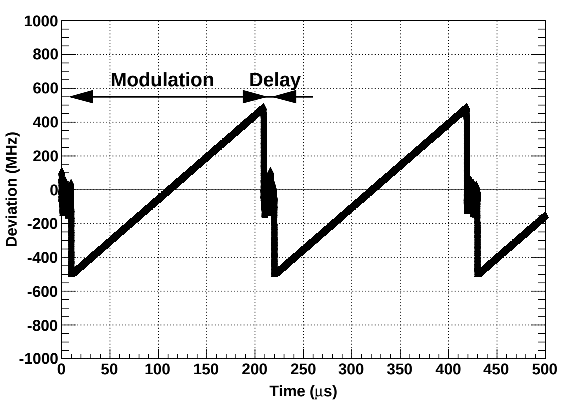

Fig. 12. Measured FMCW radar signal in the time-domain.

VI. CONCLUSION

In this study, we succeeded in developing a simple and affordable 79 GHz FMCW radar evaluation system based on the PLL-Gunn oscillator and fundamental mixer. The PLL-Gunn oscillator has a frequency accuracy of 0.13 ppm, a phase noise of -53.3 dBc/Hz at the 1 kHz offset, and an output power of 11.7 dBm. The down-converter has a typical conversion-gain of 7.8 dB and a noise figure of 14.8 dB. The down-converter linearity is kept up to the input power of 3 dBm at the center frequency of 79 GHz. The system is easy to handle and can evaluate the chirp width, chirp length, chirp rate, and linearity. These evaluations are configured in Table II at the receiving power of -56 dBm-EIRP, using a real-time spectrum analyzer in a mixed domain oscilloscope or a conventional digital oscilloscope with a signal analysis software.

By employing the evaluation system, the estimated initial cost of the implementation is approximately one-third that of a current test system. Furthermore, to improve performance, we are preparing a down-converter module combined with the PLL-Gunn oscillator and the fundamental mixer to make it more compact and cost effective, as shown in Fig. 13. The size will be 70 $\times$ 70 $\times$ 20 mm.

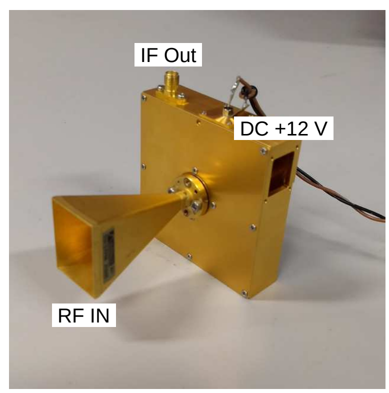

Fig. 13. Developing the 79 GHz down-converter module.

ACKNOWLEDGMENT

The authors would like to thank Dr. Atsushi Kanno at National Institute of Information and Communications Technology for the productive discussions.

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