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Design and Performance of a 24 GHz Band FM-CW Radar System and Its Application

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***Abstract*—This paper describes a design and performance of a FM-CW (Frequency Modulated Continuous Wave) radar system using 24 GHz band. The principle for measuring the distance and the small displacement of target object is described, and the differential detection method for detecting the only target is proposed under the environments which multiple objects are located. In computer simulation, the basic performance of FM-CW radar system is analyzed about the distance resolution and error value according to the various sampling time and sweep bandwidth. Furthermore, the FM-CW radar system with the proposed differential detection method can clearly detect only the target object under the multiple object environment, and the small displacement within 3.11 mm can be measured. In experiment, the performance about measuring the distance and displacement is described by using the designed 24 GHz FM-CW radar system. As the results, it is confirmed that 24 GHz FM-CW radar system with the proposed differential detection method is effective for measuring target under the environments which multiple objects are located.**

I. Introduction

Radar systems with 24 GHz band is based on ARIB standard T73 [1] as sensors for detecting or measuring mobile objects for specified low power radio station. And the 24 GHz band radar system can be applied in various field such as security, medical imaging and so on under indoor and outdoor environments. There are various radar systems have been proposed [2], [3], [4], [5]. The pulsed radar system measures the period between the signal is transmitted and received. The pulsed radar can detect the distance in far field, however, the target in near field can not be detected correctly. The Doppler radar system measures the frequency difference between the reflected and transmitted signals. The Doppler radar can detect the moving velocity of the target, however, the distance of the target can not be detected. The FM-CW (Frequency-Modulated Continuous-Wave) radar system [6], [7] is the most widely used for detecting the distance of the target object in near field and the small displacement of the target.

In this paper, we used and developed the 24 GHz FM-CW radar system for measuring the distance and displacement of an object when the object is static or moves very slowly. The basic performance of the 24 GHz FM-CW radar system for measuring a target object is analyzed by using the computer simulation. Moreover, we proposed the differential detection method for signal processing in the FM-CW radar system in order to detect only the target object under the environments which multiple objects are located. Furthermore, an example of application with the 24 GHz FM-CW radar system is shown in experiment.

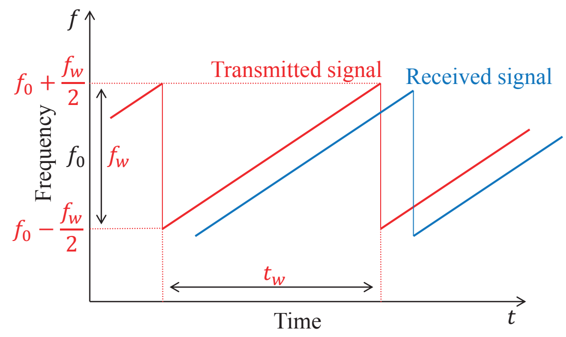


Fig. 1. Sawtooth frequency modulation.

This paper consists of the following sections. Section II describes the principle of a FM-CW radar system. Section III describes and analyses the basic performance and the proposed differential detection method in computer simulation. Section IV shows the experimental results with 24 GHz FM-CW radar system. Finally, Section V concludes this paper.

II. Principle for FMCW radar

FM-CW (Frequency-Modulated Continuous-Wave) radar is a radar transmitting a continuous carrier modulated by a periodic function such as a sawtooth wave to provide range data shown in Fig. 1. Fig. 2 shows the block diagram of a FM-CW radar system [8].

In the FM-CW radar system, frequency modulated signal at the VCO is transmitted from the transmitter Tx, then signals reflected from the targets are received at the receiver Rx. Transmitted and received signals are multiplied by a mixer, and beat signals are generated as multiplying the two signals. The beat signal pass through a low pass filter, then an output signal is obtained. In this process, the frequency of the input signal is varied with time at the VCO. The modulation waveform with a linear sawtooth pattern [9] as shown in Fig. 1. This figure illustrates frequency-time relation in the FM-CW radar, and the red line denotes the transmitted signal and the blue line denotes the received signal. Here, f_0 denotes the center frequency, f_{w} denotes the frequency bandwidth for sweep, and t_w denotes the period for sweep.

We define that the transmitting signal $V_{\mathrm{T}}(f, x)$ at the transmitter Tx in Fig. 2 is represented as

$$V_{\mathrm{T}}(f, x) = A\mathrm{e}^{j\frac{2\pi f}{c}x} \quad , \tag{1}$$

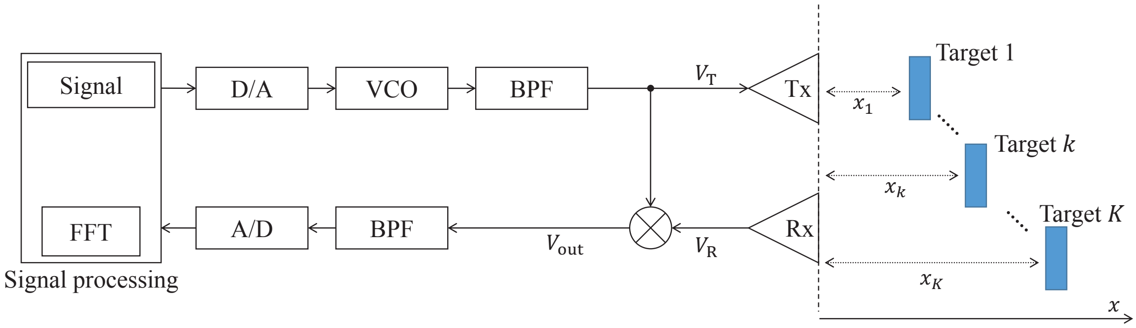


Fig. 2. Block diagram of a FM-CW radar system.

where f denotes a frequency at a time, x denotes a distance between a target and the transmitter, A denotes an amplitude value and c denotes the speed of light.

The reflected signal $V_R(f,x)$ at the receiver Rx in Fig. 2 is represented as

$$V_{\mathrm{R}}(f,x) = \sum_{k=1}^{K} A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi f}{c}(2d_k - x)} \quad , \tag{2}$$

where γ_k and φ_k are the reflectivity coefficients for amplitude and phase on kth target, respectively. α_k, denotes amplitude coefficient for transmission loss from kth target, and d_k is the distance between the transmitter and the kth target.

Here, at the receiver whose position is $x = 0$, Eq. (2) is rewritten as

$$V_{\mathrm{R}}(f,0) = \sum_{k=1}^{K} A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi f}{c}(2d_k)} \quad . \tag{3}$$

The beat signal are generated as multiplying the transmitted signal in Eq. (1) and the received signal in Eq. (3) at the position $x = 0$. After LPF, the output signal $V_{\mathrm{out}}(f,0)$ is generated by

$$V_{\mathrm{out}}(f,0) = \sum_{k=1}^{K} A^2\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f d_k}{c}} \quad . \tag{4}$$

By using signal processing, a distance and a displacement for the target are given from the generated output signal in Eq. (4). By using the Fourier transform, the distance spectrum of the output signal $P(x)$ is calculated as follow.

$$\begin{aligned} P(x) &= \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} V_{\mathrm{out}} e^{-j\frac{4\pi f}{c}} df \\ &= \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} \sum_{k=1}^{K} A^2\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f d_k}{c}} e^{-j\frac{4\pi f x}{c}} df \\ &= A^2 \sum_{k=1}^{K} \alpha_k\gamma_k e^{j\varphi_k} \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} e^{j\frac{4\pi f(d_k-x)}{c}} df \\ &= A^2 \sum_{k=1}^{K} \alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f_0(d_k-x)}{c}} f_w \frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}} \quad . \end{aligned} \tag{5}$$

The amplitude value of the distance spectrum $|P(x)|$ in Eq. (5) is given as

$$\begin{aligned} |P(x)| &= A^2 \left| \sum_{k=1}^{K} \alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f_0(d_k-x)}{c}} f_w \frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}} \right| \\ &\leq A^2 f_w \sum_{k=1}^{K} \alpha_k\gamma_k \left| \frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}} \right| \quad , \end{aligned} \tag{6}$$

and we have equality if and only if the phase components $\phi_k + \frac{4\pi f_0(d_k-x)}{c}$ about all of k are equal.

Here, we assumed that the number of target is 1. The distance spectrum in Eq. (5) is rewritten as

$$P(x) = A^2\alpha_1\gamma_1 e^{j\varphi_1} e^{j\frac{4\pi f_0(d_1-x)}{c}} f_w \frac{\sin\left\{\frac{2\pi f_w(d_1-x)}{c}\right\}}{\frac{2\pi f_w(d_1-x)}{c}} \quad , \tag{7}$$

and the amplitude value of distance spectrum is given as

$$|P(x)| = A^2\alpha_1\gamma_1 f_w \left| \frac{\sin\left\{\frac{2\pi f_w(d_1-x)}{c}\right\}}{\frac{2\pi f_w(d_1-x)}{c}} \right| \quad . \tag{8}$$

This equation indicates that the distance for the target is generated by the amplitude value of distance spectrum.

The phase value of distance spectrum $\angle P(x)$ is represented as

$$\angle P(x) = \varphi_1 + \frac{4\pi f_0(d_1 - x)}{c} = \theta_1(x) \quad . \tag{9}$$

Here, $\theta_1(x)$ satisfy $-\pi \leq \theta_1(x) \leq \pi$, then the displacement for the target is

$$-\frac{c(-\pi - \varphi_1)}{4\pi f_0} \leq d_1 \leq \frac{c(\pi - \varphi_1)}{4\pi f_0} \quad . \tag{10}$$

If the phase value satisfies $\phi_1 = 0$, Eq. (10) is rewritten as -3.11 [mm] $\leq d_1 \leq +3.11$ [mm] with $f_0 = 24.15$ [GHz]. That is, the small displacement of the target within ± 3.11 [mm] is generated by the phase value of distance spectrum.

TABLE I. PARAMETERS IN COMPUTER SIMULATIONS

Parameters	Value
Center frequency	24.15 GHz
Bandwidth	50, 100, 200, 400 MHz
Sweep time	1024 μs
Sampling time of sweep	0.1, 1, 10 μs
Number of FFT points	4096
Window function	hamming

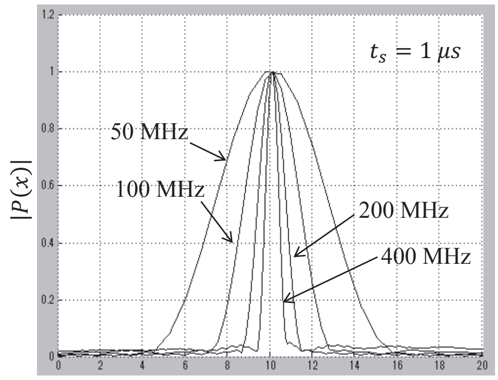


Fig. 3. Resolution for distance spectrum according to sweep bandwidth.

On the other hands, the maximum distance for measuring $d_{\max}$ is

$$\Delta f = \frac{f_w}{t_w/t_s}[\text{Hz}] \quad ,$$
$$d_{\max} = \frac{c}{4\Delta f}[\text{m}] \quad , \tag{11}$$

where t_w denotes the sweep time, t_s denotes the interval time for sampling. For example, in the case with t_w = 1024 [μs] and t_s = 1 [μs], the maximum distance is $d_{\max}$ = 384 [m].

III. Computer Simulation

A. Basic Performance

At first, we describes the basic performance about the FM-CW radar with 24 GHz band. Parameters for computer simulation are listed in Table I. Center frequency is 24.15 GHz, bandwidth are 50, 100, 200, and 400 MHz. Note that the 400 MHz bandwidth is only used for the computer simulation because of standards in the Radio Law in Japan. Sweep time is 1024 μs, sampling times of sweep are 0.1, 1, 10 μs, number of FFT points is 4096, and the hamming windows is adapted as the window function in signal processing.

We assumed that a static target is located at 10 m from the transmitter and receiver, and the distance spectrums are outputted with various parameters. Fig. 3 shows the amplitude value for distance spectrum versus measured distance with various sweep bandwidth. The result shows that the sweep bandwidth influences the distance resolutions and widely bandwidth can improve the resolution. In the case with t_s = 1 μs, the distance resolutions with f_w = 50, 100, 200, 400 MHz are ±5, ±1.5, ±1, ±0.5 m, respectively. Fig. 4 shows the amplitude value for distance spectrum versus measured distance with various sampling time. The result shows that

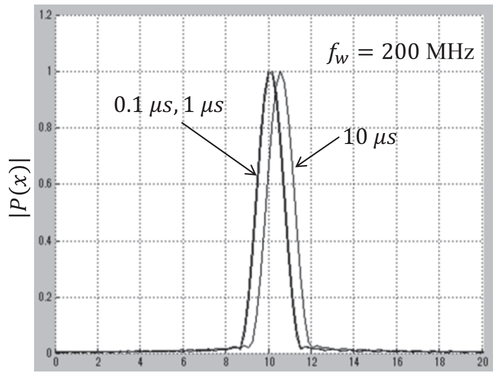
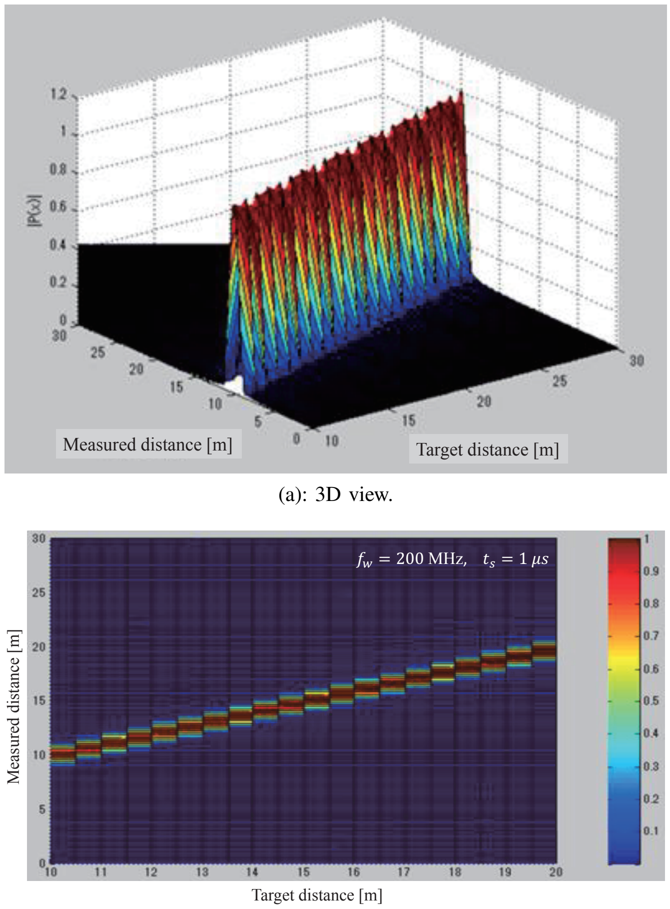


Fig. 4. Error value for distance spectrum according to sampling interval.



(a): 3D view.

(b): 2D view.

Fig. 5. Distance spectrum for measuring moving target.

the sampling interval influences the error about the measured distance and shortly sampling interval can reduce the error value for distance. In the case with f_w = 200 MHz, the error values about the measured distance with t_s = 10 μs is about 0.5 m.

Fig. 5 shows the result for measuring a slowly moving target with f_w = 200 MHz and t_s = 1 μs. The target moved from 10 m to 20 m at intervals of 0.5 m. Fig. 5(a) shows

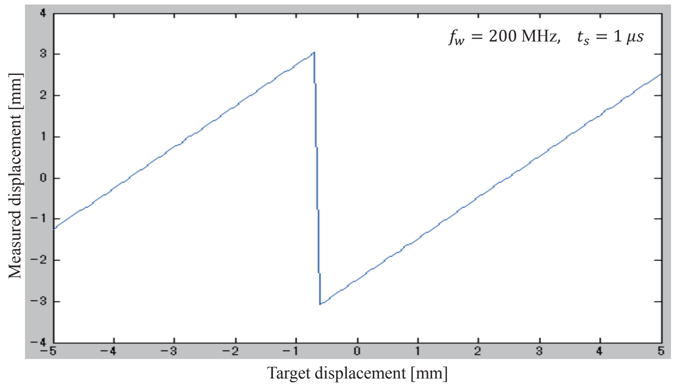


Fig. 6. Measured displacement.

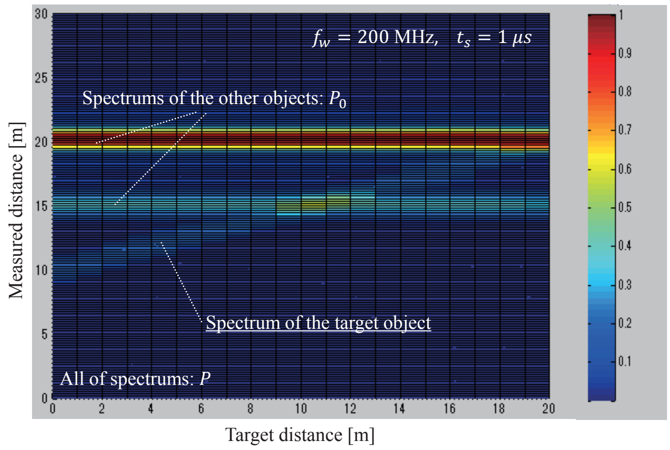
the amplitude value versus measured distance versus target distance with 3-dimensional viewing, and Fig. 5(b) shows measured distance versus target distance with 2-dimensional viewing. The color in (b) is corresponding to the strength of the amplitude value in (a). From these figures, it is confirmed that the distance can be measured correctly according to the positions of the moving target.

Fig. 6 shows the result for measuring a target with small displacement, and the measured displacement versus target displacement is outputted. The object is located at 10 m from the receiver, and the object moved from -5 mm to 5 mm at intervals of 0.1 mm. The small displacement can be measured by the phase value of distance spectrum, and the measured displacement is corresponding to the target displacement. Note that the measured displacement denotes the relative displacement and it is not corresponding to the absolute distance between the receiver and the target object. The small displacement within $\pm$ 3.11 mm is correctly measured with the parameters of the FM-CW radar system in this paper, however, the displacement more than $\pm$3.11 mm has uncertainty.

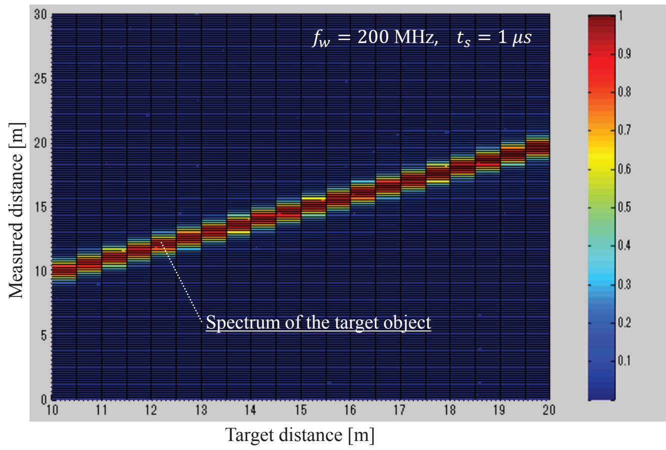
B. Proposed target detection

As mentioned in the above section, the FM-CW radar system can measure the distance and the small displacement for 1 target object. However, it is a special case that only the reflected signal on a target can be received at the receiver. In general, the receiver may receive the reflected signals from many objects. Therefore, when there is some objects for measuring the target distance, signal processing for detecting the distance spectrum from the only target is required.

The proposed method removes the signals from the other objects by using the differential detection of distance spectrum. Fig. 7 shows the distance spectrum when the target object moves from 10 m to 20 m and the other objects are located at 15 m and 20 m. The transmitted signal is reflected on the target and the other objects, the receiver receives several reflected signals. Therefore, the distance spectrum of the other objects are also generated by the FM-CW radar system in Fig. 7(a), and the distance spectrum of the target can not be detected clearly. In particular, when the reflection coefficient of the target is lower than that of the other objects, the distance spectrum of the other object has higher amplitude value than that of the target.



(a): without differential detection.



(b): with differential detection (Proposed).

Fig. 7. Distance spectrum for measuring moving target distance with / without the differential detection under the environments which multiple objects are located.

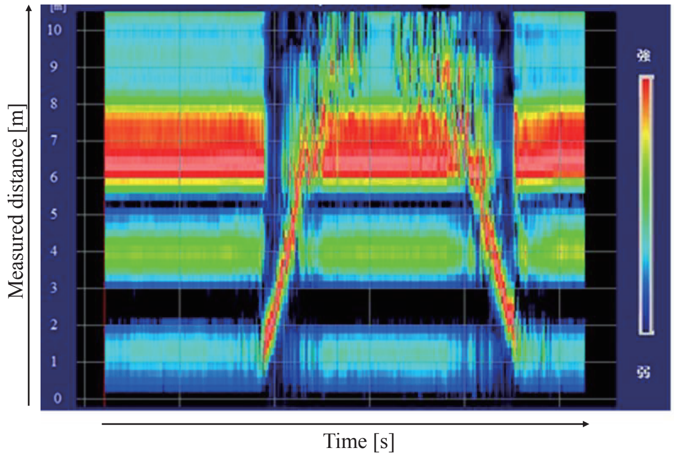
In the proposed differential detection, at first, the distance spectrum of the other objects P_0 is generated beforehand in Fig. 7(a). Then, the distance spectrum of the target and the other object P is subtracted by P_0. By using the differential detection, distance spectrum removed the distance spectrum of the other targets is generated as $P - P_0$. Therefore, the distance spectrum of the desired target is only detected. Fig. 7(b) shows the distance spectrum by using the proposed differential detection method, and the distance spectrum of the target is correctly measured. As compared with the measured distance spectrums in Fig. 7(a) and (b), it is clearly confirmed that the proposed method can detect target distance by using the difference detection. The proposed differential detection can effectively detect the moving or static target distance from multiple reflections of the background static objects.

IV. Experiments

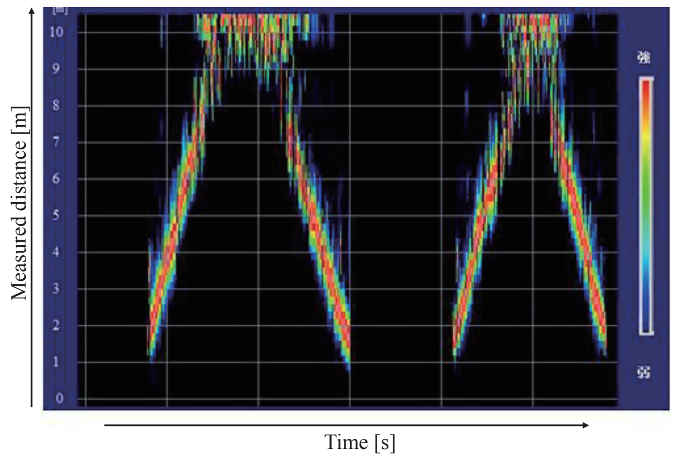
In order to evaluate the effectiveness of the proposed method for detecting the target distance and displacement, we develop a FM-CW radar system and carried out the experiments with the radar system in actual environment. Table II lists the parameters, and the developed FM-CW radar system get a certificate of conformity with technical regulations in

TABLE II. PARAMETERS IN EXPERIMENTS

Parameters	Value
Center frequency f_0	24.15 GHz
Sweep bandwidth f_w	200 MHz
Sweep time t_w	1024 μs
Sampling time of sweep t_s	1 μs
Transmitter power output	0.007 W
Antenna gain	11 dBi
Range of distance	0 – 100 m
Range of relative displacement	$\pm$3.11 mm



(a): without differential detection.



(b): with differential detection (Proposed).

Fig. 8. Distance spectrum for measuring moving target distance with / without the differential detection.

Article 38-6 Paragraph 1 of the Radio Law in Japan, and developed FM-CW radar system is accommodate to ARIB standard T73 in Japan [1].

A. Distance Spectrum

Fig. 8 shows the distance spectrum of a moving target. A person walked away from the FM-CW radar and then came close between 2 [m] to 10 [m]. In Fig. 8(a), several distance spectrums of the person and the background objects are outputted. The distance spectrum of the moving person is not clearly detected in Fig. 8(a). In order to detect the distance spectrum of the moving person with the differential detection method, the distance spectrum without the person is measured beforehand. By generating the distance spectrum of the background objects beforehand, the distance spectrum of the moving person is correctly detected in Fig. 8(b) with the proposed differential detection. Therefore, the FM-CW radar system can measure movement of the target person effectively.

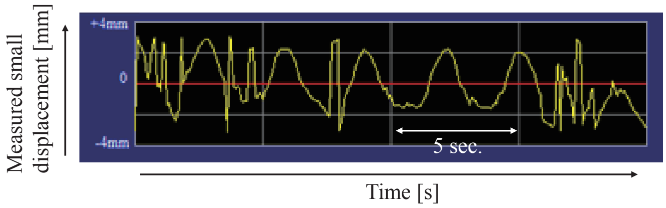


Fig. 9. Displacement for measuring the movement of human breathing.

Fig. 10. Setup of FM-CW Radar for detecting human breathing.

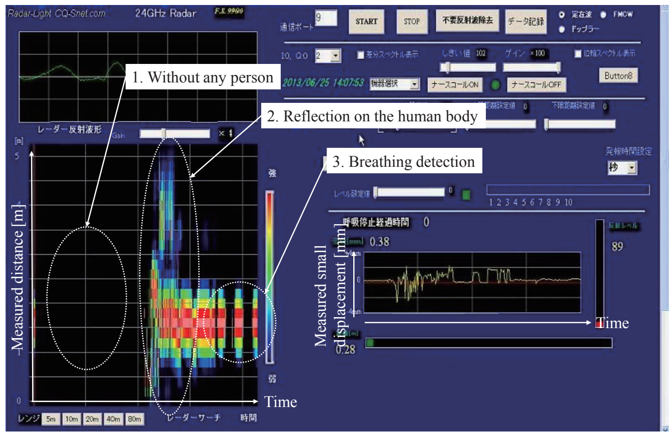


Fig. 11. Example of application.

Fig. 9 shows the result of measuring the small displacement for human breathing. The human's chest movement is measured within the range of relative small displacement. In Fig. 9, it is detected that the period of breathing is about 4 [s] and the breathing movement is about within $\pm$2 [mm].

B. Example for application

Finally, we show an example of application with 24 GHz FM-CW radar system. Fig. 10 shows a setup of the FM-CW radar system for detecting human breathing in actual environments. The FM-CW radar satisfies the safety guideline, and the details of the safety guideline is described in Appendix.

Fig. 11 shows the example for detecting human breathing.

The distance spectrum in this example is measured as following flow.

1) Measuring distance spectrum without any person.
2) A person comes to the bed. The radar received signals from human's body.
3) The person lies asleep on the bed. The radar detects the person's breathing movement.

By generating the distance spectrum of the background objects without the person, the distance spectrum of the person is only detected. When the person comes within the range of radar, the radar system can detect reflected signals from the person, and the distance spectrums of the human's body are detected. After the person lies on the bed, the radar system can detect the small displacement for the person's breathing movement. By using the differential detection method, the distance and small displacement of the moving object is clearly detected.

V. Conclusion

In this paper, design and performance of a FM-CW radar system with 24 GHz band is described. In computer simulations, basic performances of FM-CW radar system is analyzed about the distance resolution and error value according to the sweep time and the sampling interval, respectively. Moreover, the differential detection method for detecting only the target object is proposed for measuring the distance and the displacement of the target under the environments which multiple objects are located. In experiments, the distance spectrum of the target object is clearly detected by using the differential detection method under the environments which multiple objects are located. Furthermore, an example of application for detecting human's breathing movement is shown. As the result, the 24 GHz FM-CW radar with the proposed differential detection method effectively detect the distance and the small displacement under the environments which multiple objects are located.

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Appendix

In general, electromagnetic wave must be satisfied the guidelines on human exposure to electromagnetic fields, where it have been instituted in various organizations. IEEE C95.1 in USA [10] and ICNIRP in Europe are the guidelines, and MIC also have instituted the guideline in Japan [11].

Developed 24 GHz FM-CW radar in this paper have the properties as follow. The power of the transmitter is 7 [mW], the transmitting antenna gain is 11 [dBi], the effective radiated power is 88 [mW], the radiation angle of the transmitting wave is about 50 [degree], and the distance between the transmitter and the human is 2.5 [m]. According to the radar equation, the electric field strength E and the power density P on the human body is calculated as

$$
\begin{aligned}
E &= \sqrt{\frac{30 \times 0.088}{2.5}} = 0.65 \ [\mathrm{V/m}] \quad , \\
P &= \frac{E^2}{z_0} = \frac{0.65^2}{120\pi} = 1.12 \times 10^{-4} \ [\mathrm{mW/cm^2}] \quad .
\end{aligned}
$$

According to the guideline [11], these parameters must be satisfied as

$$
\begin{aligned}
E &\leq 61.4 \ [\mathrm{V/m}] \quad , \\
P &\leq 1 \ [\mathrm{mW/cm^2}] \quad .
\end{aligned}
$$

Therefore, the developed 24 GHz FM-CW radar system in this paper sufficiently satisfies the conditions in the guideline.