Development of Millimeter Wave Radar using Stepped Multiple Frequency Complementary Phase Code and Concept of MIMO Configuration

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***Abstract*— Stepped multiple frequency Complementary Phase Code (CPC) modulation proposed by authors is a unique radar modulation/demodulation method that can achieve an extremely low range sidelobe by the short code length, a high range resolution equivalent to the transmission bandwidth by a narrower band receiver, and a long range detection performance. Authors also have developed 60GHz millimeter wave radar employing this modulation. In this paper, the experimental results using the radar system are at first presented to verify the radar performance described above. Then the concept of expansion to Multi Input Multi Output (MIMO) of stepped multiple frequency CPC is also described. The initial simulation results indicated the possibility that MIMO stepped multiple frequency CPC enable us to obtain not only a high range-velocity resolution but also a high angular resolution while preventing the deterioration of the characteristics in Doppler direction.**

Keywords—Radar; Modulation; Stepped multiple frequency CPC; MIMO; Complete Complementary Code;

I. INTRODUCTION

Frequency Modulation Continuous Wave (FMCW) radar, which provides a high range resolution with relatively low computation load, is widely employed for current automotive radar systems. However, the miss-pairing of the detected beat-frequency in the up and down sweeps of FMCW tend to cause a problem under the multiple target situations in principle [1]. Pulse compression [2] is another common technique to realize a high range resolution equivalent to the transmission bandwidth without the pairing process. Meanwhile pulse compression generally needs the wide band receiver to accomplish the high range resolution, which decreases S/N ratio and requires a heavy computational load. The peak sidelobe depends on the number of the code length.

From the background described above, we have proposed Stepped multiple frequency complementary phase code (CPC) modulation [3]. The synthetic bandwidth processing subsequent to CPC pulse compression and Pulse Doppler Filter (PDF) achieves a high Doppler resolution and high range resolution equivalent to the transmission bandwidth by a narrow band receiver. That is why this method has long range detection performance [4]. This method also made it possible to obtain the extremely low range sidelobe by the short code length in CPC pulse compression. Authors have developed and are developing 60GHz, 76GHz, and 79GHz millimeter wave radars using stepped multiple frequency CPC, respectively. These millimeter wave radars meet the specified low-power radio station standard of the millimeter wave in Japan.

To improve the localization performance of the radar system, we are considering the method to operate two or more radars using Stepped multiple frequency CPC simultaneously. An example of utilizing multiple radars is multi-static radar network where the radar systems are located and operated separately to cover larger area and improve localization performance. The other example is Multi Input Multi Output (MIMO) radar which consist the virtual array using multiple transmitters and receivers. In this paper, the concept of MIMO Stepped multiple frequency CPC that employs Complete Complementary Code (CCC) [5] is described. This expansion are considered to be applied to multi-static Stepped multiple frequency CPC. In this paper, at first Stepped multiple frequency CPC modulation/demodulation is described. Then the experimental verifications using 60GHz millimeter wave radar are presented. The concept of MIMO Stepped multiple frequency CPC using CCC and the initial simulation results of MIMO stepped multiple frequency CPC are also shown.

II. STEPPED MULTIPLE FREQUENCY CPC RADAR

Stepped multiple frequency CPC modulation is a hybrid method of synthetic bandwidth (Synthetic Wideband Waveform (SWW)) [6], Pulse Compression (PC), and PDF. Fig.1 (a) and (b) show the beat frequency of up and down sweep of FMCW radar for a moving single target in situation where many stationary objects exist. Fig.1 (c) and (d) show result of PDF of each frequency step (n=0 and n=1) of proposed method. As described in introduction, FMCW

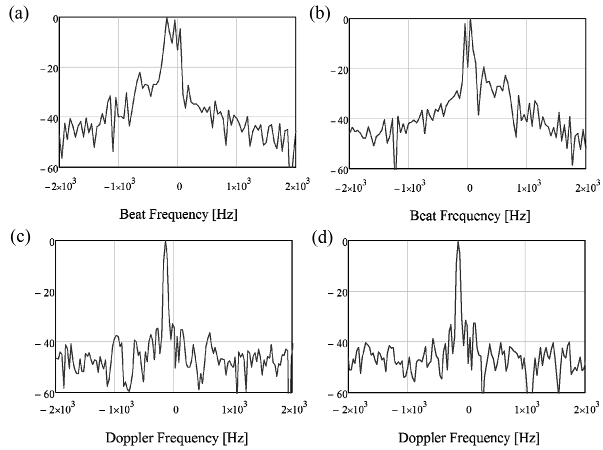

Fig.1 Example of experimental results of FMCW beat frequency and Doppler frequency from PDF for single moving target in environment where many stationary objects exist (a) up-sweep of FMCW, (b) down-sweep of FMCW, (c) PDF result of proposed method (n=0), (d) PDF result of proposed method (n=1).

suffers in multiple target situations. The floor level is increased by stationary objects and many peaks are exist, which cause miss-pairing. On the other hand, proposed method can separate the moving target from stationary objects. In addition, this method adopts CPC pulses for the pulse compression. As shown in Fig.2 (a), the pair of CPC pulses which satisfy the complementary condition each other are transmitted on the same carrier frequency. The carrier frequencies are changed N times step-like in a sequence. The same sequences are repeated M times.

A. Block diagram of signal processing of Stepped multiple frequency CPC radar

Fig.2 (b) shows the block diagram of the signal processing of Stepped multiple frequency CPC. After Pulse Compression (PC) process, Doppler frequencies which correspond to the relative velocities of targets are estimated by FFT in pulse hit direction m on the same range bin. This process corresponds to PDF of Pulse compression radar. The CPC pulse compression that provides the range gate with extremely low range side-lobe is composed of PC, Compensation of phase shift by Doppler, and ADD process. Finally, SWW using the output of ADD process as the input produces Range-Doppler map with a high range resolution equivalent to the transmission bandwidth by a narrower band receiver compared with the transmission bandwidth.

Signal processing of Stepped multiple frequency CPC

As in the case with pulse compression radar, PC is done by the cross correlation between the received signal $R[code,n,m,s]$ and reference signal $Ref[code,n,m,s]$ for each PRI. That is denoted by the function of sequence number m and frequency step n, and complementary code ($code$ = 0, 1), and range bin s.

$$PC[code,n,m,s] = \Im^{-1}(\Im(R)\cdot\Im(Ref)) \quad (1)$$

$\Im(*)$ denotes Fourier transform. PDF is also performed by FFT in sequence direction (m direction in Fig.2 (a)) on the same range bin and same frequency step, which is described by (2).

$$PD[code,n,m,s] = \sum_{k=0}^{M-1} PC[code,n,m,s]\cdot\exp\left(-2\pi j\cdot\left(\frac{m}{M}k\right)\right) \quad (2)$$

where the detectable maximum velocity $Vmax$ is given by (8).

$$V\max = \frac{c}{4\cdot PRI\cdot Code\cdot N} \quad (3)$$

$Vmax$ is inversely proportional to $Code$. That is why we adopt $Code$=2, which is the minimum number that can form complementary condition. CPC pulse compression generally suffers from the phase shift due to the Doppler frequency [7]. Stepped multiple frequency CPC has the compensation process for the phase shift.

$$PHC[code,n,m,s] = PD\cdot\exp\left\{2\pi j\frac{m}{2MN\cdot PRI}\left(s+PRI\cdot(2n+code)\right)\right\} \quad (4)$$

After the compensation process, CPC pulse compression is completed by ADD process where the output for code 1 is added by that for code 2 each other.

$$ADD[n,m,s] = \sum_{code=0}^{1} PHC[code,n,m,s] \quad (5)$$

As a result, the range profile has extremely low range side-lobe. Finally, SWW, which is realized by FFT in frequency direction (n direction) produces a high range resolution equivalent to the transmission bandwidth by a narrower band receiver compared with the transmission bandwidth.

$$SWW[m,s'] = \sum_{n=0}^{N-1} ADD[n,m,s]\exp\left(j\cdot\left(\frac{4\pi\cdot s'\cdot\Delta R}{c}n\cdot\Delta f\right)\right)$$
$$s' = N\cdot s + n \quad (6)$$

We have an option to obtain range profile corresponding Doppler bin m with higher resolution by using super resolution method such as MUSIC for the short range instead of SWW [8], which called Super Resolution mode (SR).

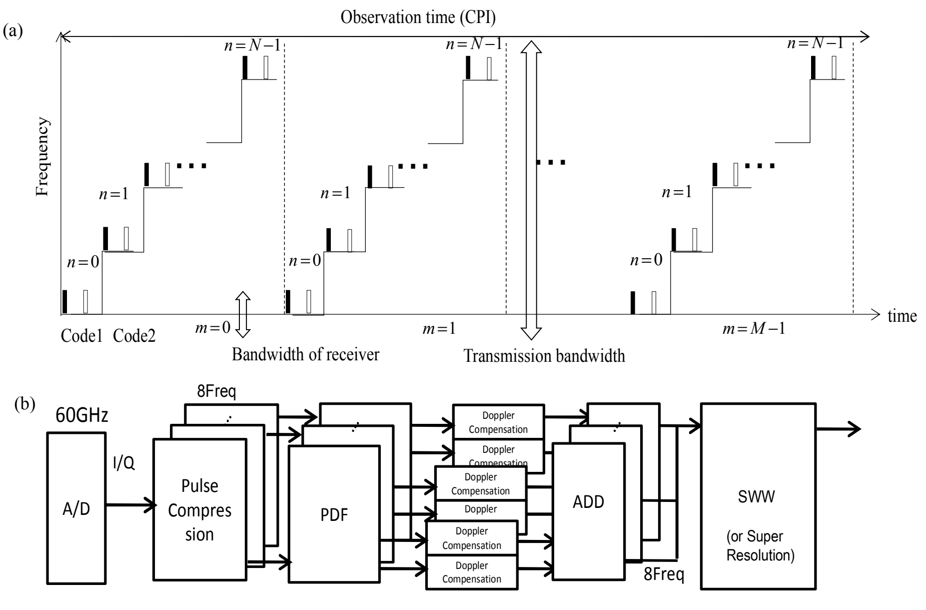

Fig.2 Stepped multiple frequency CPC modulation / demodulation method ((a) Transmitting sequence of stepped multiple frequency CPC, (b) Schematic diagram of the signal processing)

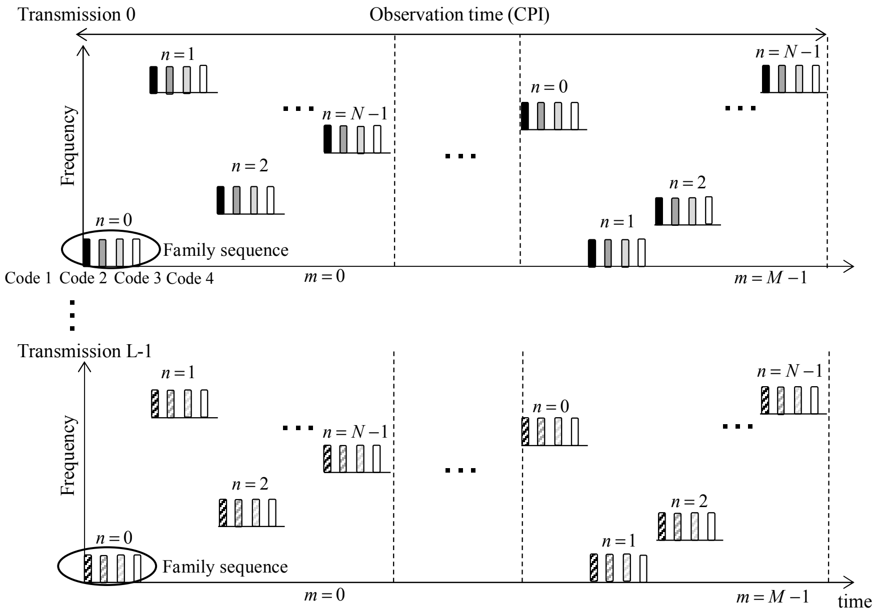

Fig.3 The random frequency step sequence of Stepped multiple frequency CPC for detectable velocity expansion.

A. Consept of MIMO Stepped multiple frequency CPC

In this section, we consider employing CCC for MIMO expansion. CCC is also a kind of complementary codes [5]. That has ideal auto- and cross-correlation properties. CCC is a collection of code sequence sets with the property that the sum of the auto-correlation between family sequence sets is zero except for zero shift (τ=0) and the sum of cross-correlation between other family sequences is zero for all shifts as described by (7) and (8).

$$PC[k,l,code,n,m,s]=\sum_{s=0}^{S-1}R[k,code,n,m,s]\cdot Ref[l,s+\tau]^{*} \qquad (7)$$

$$ADD[n,m,s]=\sum_{code=0}^{CODE-1}PHC[k,l,code,n,m,s]=\begin{cases}CODE\cdot S\cdot\delta(s) & k=l\\ 0 & k\neq l\end{cases} \qquad (8)$$

where k and l $(k,l=0,1,\ldots,L-1)$ denotes the receiving and transmitting antenna, respectively. It is also known that the number of codes consisting sequence set must be larger than or equal to the number of family sequence sets ($CODE \geqq L$) [5]. Here we consider the transmission sequence using CCC in the case of 4 transmitting antennas where the numbers of family sequence sets and codes consisting sequence set are both set to be 4. The detectable maximum velocity depends on the interval of the same code on the same carrier frequency as described by (3). Thus the increasing of the number of codes consisting sequence set cause the decreasing of detectable velocity. To recover the detectable velocity, the random frequency step sequence as shown in Fig. 3 is also considered. In this case, PDF is performed by DFT instead of FFT. After ADD process, SWW process can be performed at each receiving antenna for 4 transmission antenna. Fig.4 shows a possible virtual array configuration of MIMO Stepped multiple frequency CPC. As described above, each receiver (Rx = 0, 1,.., RX-1) can extract the output of SWW from 4 different transmitter by preparing the CCC reference signals for each transmitter (Tx = 0, 1, …, TX-1). The output of SWW of each Rx for each Tx (4×4) is expected to involves the phase information associated with incident angle of the target θ_1 described as (9) regarding Rx = 0, Tx = 0 as the reference of the phase.

$$\boldsymbol{SWW}[m,s',Rx,Tx]=\begin{pmatrix}\alpha\\ \alpha\exp\left(j\frac{2\pi\cdot d_1\cdot 1\cdot\sin\theta_1}{\lambda}+j\frac{2\pi\cdot d_1\cdot 0\cdot\sin\theta_1}{\lambda}\right)\\ \vdots\\ \alpha\exp\left(j\frac{2\pi\cdot d_1\cdot Rx\cdot\sin\theta_1}{\lambda}+j\frac{2\pi\cdot d_1\cdot Tx\cdot\sin\theta_1}{\lambda}\right)\\ \vdots\\ \alpha\exp\left(j\frac{2\pi\cdot d_1\cdot(RX-1)\cdot\sin\theta_1}{\lambda}+j\frac{2\pi\cdot d_1\cdot(TX-1)\cdot\sin\theta_1}{\lambda}\right)\end{pmatrix} \qquad (9)$$

where α is a complex amplitude at the output of SWW at m and s' of Rx=0 and Tx=0. The angle information is expected to be extracted with an angular resolution of equivalent aperture of $15d_1$ ((TX×RX – 1)d_1) [9] by Digital Beam Forming (DBF) described by the inner product of array mode vector $\boldsymbol{A}$ and $\boldsymbol{SWW}$ as (10) and (11).

$$DBF(\theta)_{m,s'}=\boldsymbol{A}(\theta)^{H}\,\boldsymbol{SWW} \qquad (10)$$

$$\boldsymbol{A}(\theta)=\begin{pmatrix}\exp\left(j\frac{2\pi\cdot d_1\cdot 0\cdot\sin\theta}{\lambda}\right)\\ \vdots\\ \exp\left(j\frac{2\pi\cdot(RX\cdot TX-1)d_1\cdot\sin\theta}{\lambda}\right)\end{pmatrix} \qquad (11)$$

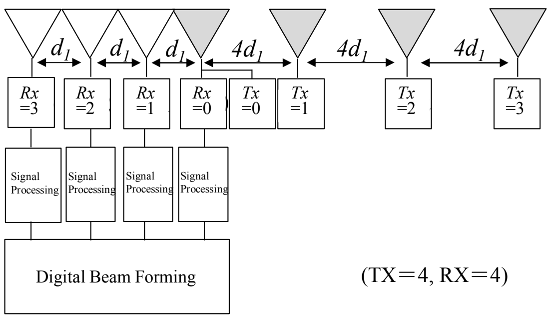

Fig.4 Array antenna configuration of MIMO Stepped multiple frequency CPC

TABLE.1 Radar parameter and expected performance

Radar Parameters	Specifications
Transmit frequency	60.32-60.67GHz
Pulse bandwidth	80MHz
Code length	16
Number of codes consisting sequence set :CODE	2
Pulse Repetition Interval (PRI)	3.5μsec
Number of Sequence Repetition: M	512
Frequency step width	50MHz
Frequency step number: N	8
Transmission bandwidth	430MHz
Observation time (CPI)	29msec
A/D sampling frequency	160MHz
Detectable Velocity	±79km/h
Velocity Resolution	0.31km/h
Range Resolution	0.34m

III. EXPERIMENTAL VERIFICATION OF STEPPED MULTIPLE FREQUENCY CPC

B. Millimeter wave radar using Stepped multiple frequency CPC

Table 1 shows the radar parameters of the millimeter wave radar using Stepped multiple frequency CPC. As shown in Fig.5 (a), the radar consists of the RF and IF unit. The radar system also has signal processing unit that operates the signal processing shown in Fig.1 (b) in real time.

C. Experimental verification results in an anechoic chamber

The experiment was conducted in an anechoic chamber as shown in Fig.5 (b). We used a corner reflector as a single target which has 10dBsm of RCS and is moved between 3.9m and 5.5m at the radial velocity of ±4km/h by an actuator. Fig.6 (a) shows the result of Doppler estimation (PDF). From Fig.6 (a), we can identify a peak associated with the velocity of -4km/h. Fig.6 (b) shows the result of ADD process. Fig.6 (b) indicates that the CPC pulse compression achieves peak side lobe level of more than 60 dB by the code length of 16, which corresponds to the code length of 1024 using m-sequence [10]. Fig.6 (c) shows the output of SWW. That result indicates that

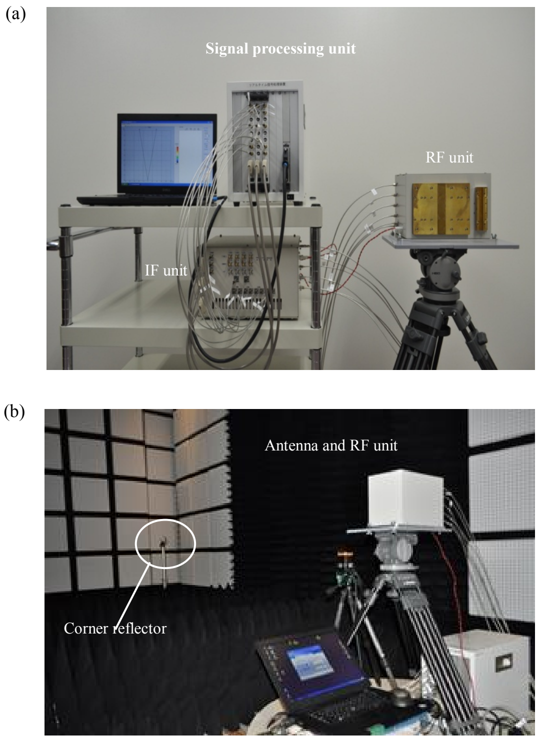

Fig.5 The experiment in an anechoic chamber ((a) Millimeter wave radar using Stepped multiple frequency CPC, (b) Experiment in an anechoic chamber using the millimeter wave radar)

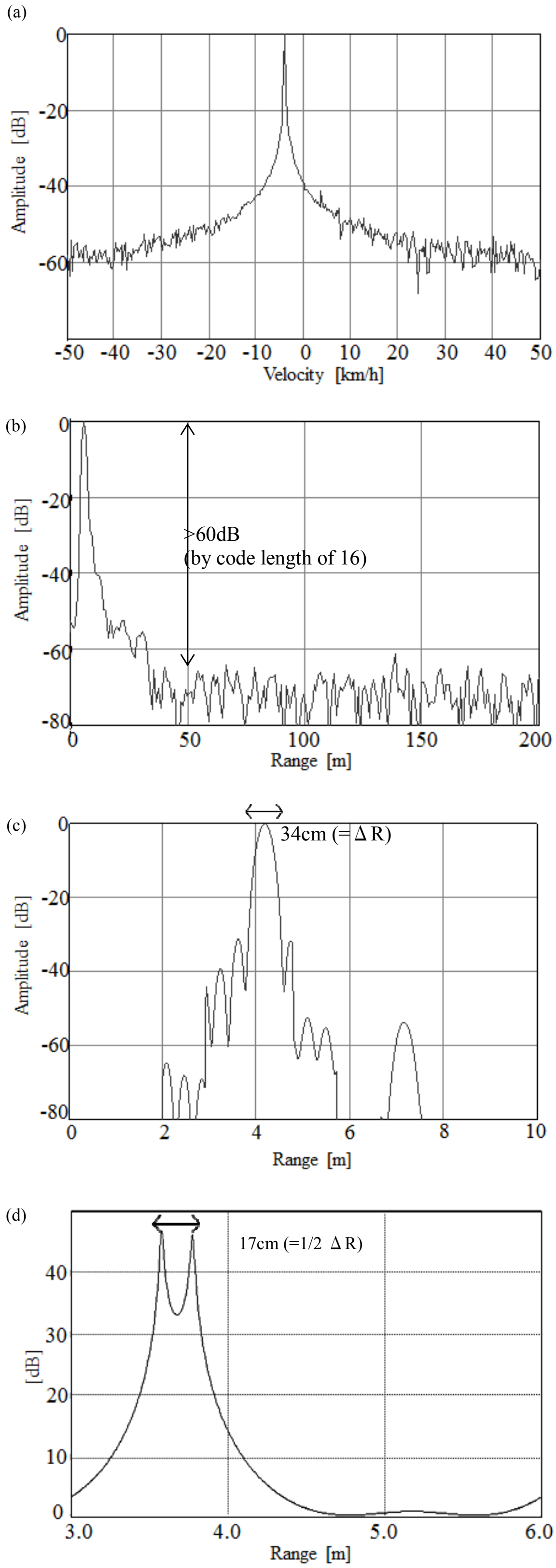

Fig.6 The experimental results ((a) Doppler estimation, (b) Result of ADD process, (c) Result of SWW process, (d) Result of SR (MUSIC) mode)).

the radar can obtain the range resolution of 0.34m which is equivalent to the bandwidth of 430MHz by using the receiver's bandwidth of 80MHz. In addition, the millimeter wave radar has SR mode for short range, where relatively high S/N is expected to be obtained. We used two corner reflectors as targets which have 10dBsm and are moved between 3.0m and 4.6m keeping the range distance of 17cm at the same velocity. Fig.6 (d) shows the results of SR mode. The range difference of 17cm correspond to 1/2 range resolution. The results indicated that Super Resolution mode could isolate the two targets located on the close range less than the range resolution.

D. Simulations of MIMO Stepped multiple frequency CPC

In the initial simulation, we employ parameters described in Table 2 and array antenna configuration shown in Fig.4. The

TABLE.2 Radar parameter of MIMO Stepped multiple frequency CPC

Radar Prameters	Specifications
Distance between antennas	0.8λ
Number of codes consisting sequence set: CODE	4
Family number: L (Number of transmission antennas: TX)	4
Number of Receiving Antenna:RX	4
Number of Sequence Repetition: M	256
Observation time	29msec
Detectable Velocity	±39km/h
Angular Resolution	4.7deg

distance between antennas d_l is set to be 0.8λ. Other radar parameters take the same value described in Table 1. The target range, velocity, and angle are set to be 12.2m, 162km/h, and 15deg respectively. The S/N at A/D is set to be 0dB. Fig 7(a) show Range-Doppler map of output of ADD process (*f*=60.32GHz) for transmission sequence described in Figs 2.

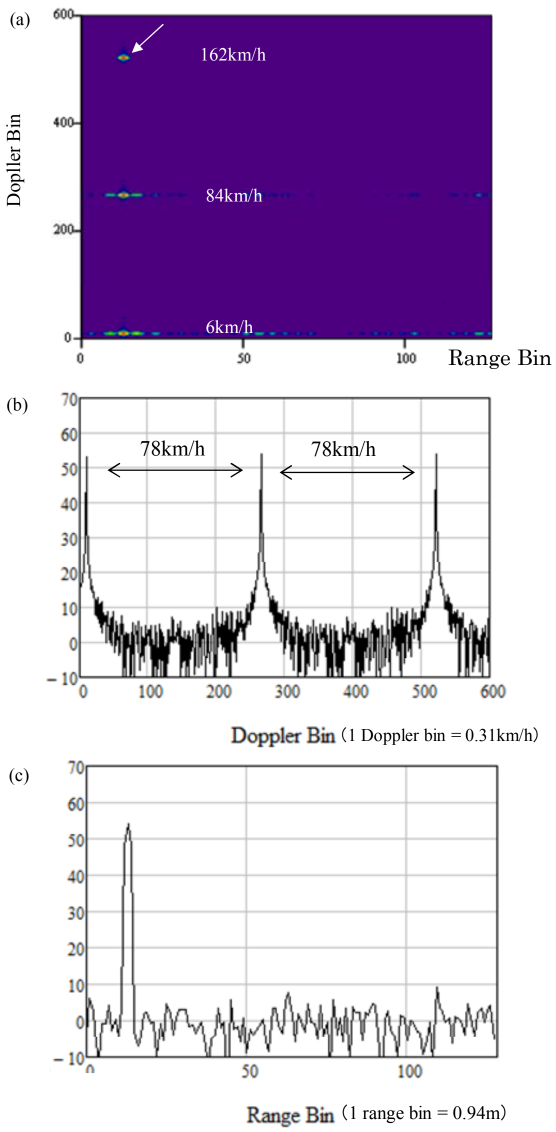

Fig.7 The Range-Doppler map at the output of ADD process of *Rx* = 0 for *Tx* = 0 using the frequency sequence of Fig.2 ((a) Range-Doppler map, (b) Doppler frequency estimation at the target range bin indicated by arrow in Fig.7 (a), (c) Range profile at the target Doppler bin indicated by arrow in Fig.7 (a).

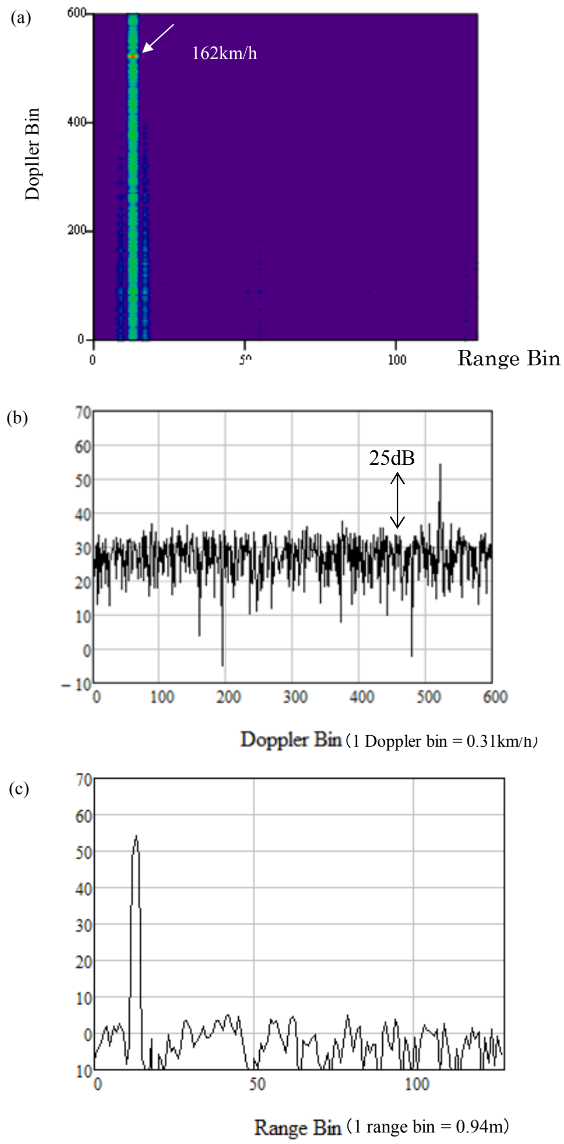

Fig.8 The Range-Doppler map at the output of ADD process of *Rx* = 0 for *Tx* = 0 using random frequency step sequence of Fig.3 ((a) Range-Doppler map, (b) Doppler frequency estimation at the target range bin indicated by arrow in Fig.8 (a), (c) Range profile at the target Doppler bin indicated by arrow in Fig.8 (a).

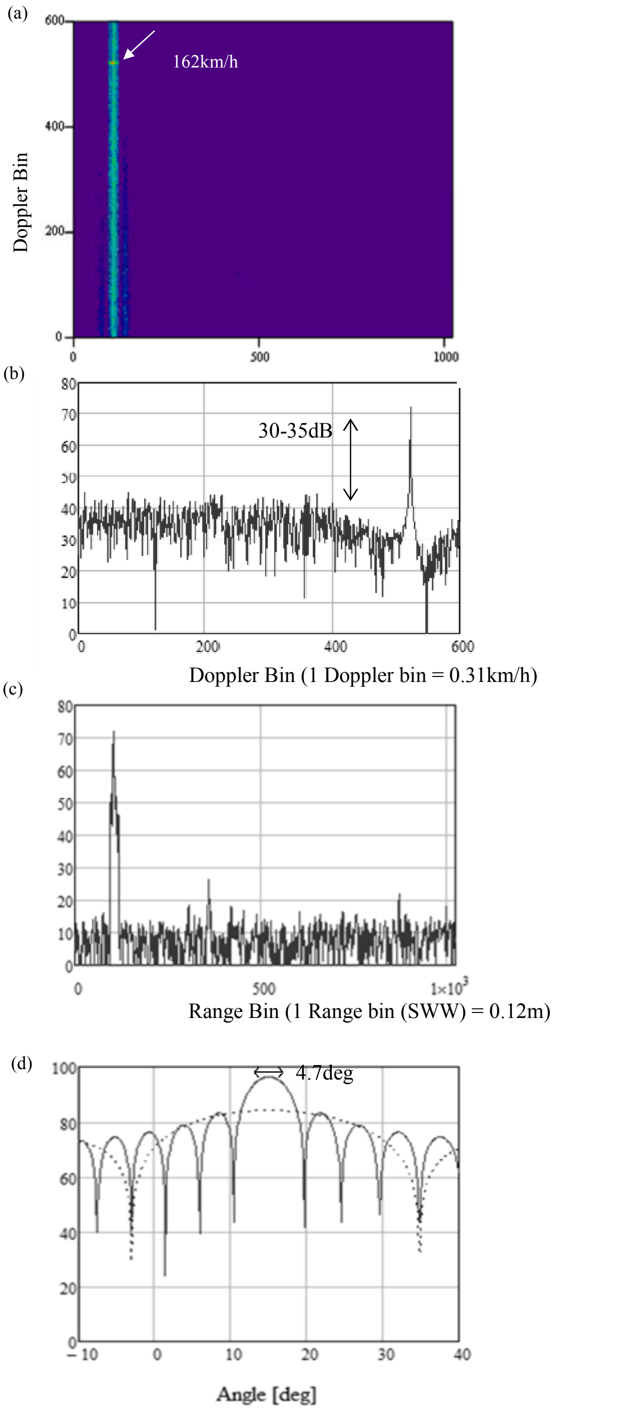

Fig.9 The output of MIMO Stepped multiple frequency CPC of $Rx = 0$ for $Tx = 0$ using random frequency step sequence of Fig.3 ((a) Range-Doppler map of SWW, (b) Doppler frequency estimation at the target range bin indicated by arrow in Fig.9(a), (c) Range profile at the target Doppler bin indicated by arrow in Fig.9 (a), (d) Angle estimation result using SWWs of 4 Tx × 4 Rx).

In Fig.7 (a), the Doppler ambiguity is identified at the interval of twice of detectable velocity. Fig. 7 (b) and (c) show the velocity estimation at the corresponding range bin and range profile at the Doppler bin pointed by an arrow in Fig.7 (a). Fig.8 (a) shows Range-Doppler map at the output of ADD process of Rx = 0 for Tx = 0 using random frequency step sequence of Fig.3. Fig.8 (b) and (c) show the velocity estimation and range profile at the corresponding bin by an arrow in Fig.8 (a). The ambiguity seems to be mitigated by the random frequency step sequence, although the peak side-lobe level in Doppler direction at the corresponding range bin seems to be limited to be about 25dB, although that in range direction is more than 60dB. Fig 9 (a) show Range-Doppler map of output of SWW process ($Rx = 0$, $Tx = 0$) of random frequency step sequence. Fig.9 (b) and (c) show the velocity estimation and range profile. The peak side-lobe level in Doppler direction is improved to 30-35dB. Finally, SWW results as shown in Fig. 10 (a) are obtained from combinations of Rx and Tx. Fig. 9 (d) shows the angle estimation result by using SWW results described by (9). In Fig.9 (d), the angular resolution is about 4.7deg that corresponds to the aperture length ($15d_1$). The dot line indicated angle estimation by 1 TX and 4 RX. The initial simulation results indicated the possibility that MIMO Stepped multiple frequency CPC enable us to obtain not only a high range-velocity resolution but also a high angular resolution.

IV. Conclusions

Authors have developed 60GHz millimeter wave radar using Stepped multiple frequency CPC. The basic performance of the radar modulation was verified by the experimental result using the millimeter wave radar. In addition, MIMO concept using CCC was also described. This expansion should be applied to multi-static configuration. The simulation results indicated that MIMO stepped multiple frequency CPC enable us to obtain not only a high range-velocity resolution but also a high angular resolution. However, the velocity expansion method described in this paper is very simple, but just an initial study. Further work for improvement of the velocity expansion of MIMO stepped multiple frequency CPC is needed.

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