Design of 24 GHz Radar with Subspace-Based Digital Beam Forming for ACC Stop-and-Go System

Seong-Hee Jeong, Jun-Nam Oh, and Kwae-Hi Lee

For an adaptive cruise control (ACC) stop-and-go system in automotive applications, three radar sensors are needed because two 24 GHz short range radars are used for object detection in an adjacent lane, and one 77 GHz long-range radar is used for object detection in the center lane. In this letter, we propose a single sensor-based 24 GHz radar with a detection capability of up to 150 m and ±30° for an ACC stop-and-go system. The developed radar is highly integrated with a high gain patch antenna, four channel receivers with GaAs RF ICs, and back-end processing board with subspace based digital beam forming algorithm.

Keywords: 24 GHz radar, 77 GHz radar, FMCW, digital beam forming, adaptive cruise control, stop-and-go.

I. Introduction

It is reported that more than 160 thousand people lose their lives and more than 6 million people are injured annually because of vehicular collision accidents all over the world [1]. Accordingly, many car makers and automobile device companies have been trying to develop a collision mitigation system for reducing the number of human casualties due to car accidents. Particularly, the adaptive cruise control (ACC) stop-and-go system is an active topic in recent development for frontal collision mitigation.

Figure 1(a) shows a general ACC stop-and-go system that requires three radar sensors: two short range radars with a maximum range of 60 m and an angle coverage up to ±30° to deal with cut-in situations, and one more long range radar with a range coverage of 150 m and an angle coverage up to ±10° to detect vehicles in the center lane [2].

DENSO has developed a 77 GHz switching array radar with a digital beam forming (DBF) structure. This radar has a range detection capability of 150 m and an angle detection capability of ±10° [3]. HELLA and M/A-Com have developed 24 GHz short-range radar with a simple monopulse structure. This radar has a range detection capability of 70 m and an angle detection capability of more than 30° [4], [5].

In this letter, to reduce the cost and size of these bulky radar systems for the ACC stop-and-go function in automotive applications, we designed a cost-effective 24 GHz single radar sensor, which has a detection capability of up to 150 m and ±30° as shown in Fig. 1(b).

II. System Design of 24 GHz Radar with DBF

In order to enhance the range and angle coverage with high resolution, the four-channel phased-array system architecture is proposed as shown in Fig. 2.

The radio frequency (RF) front-end was designed using a

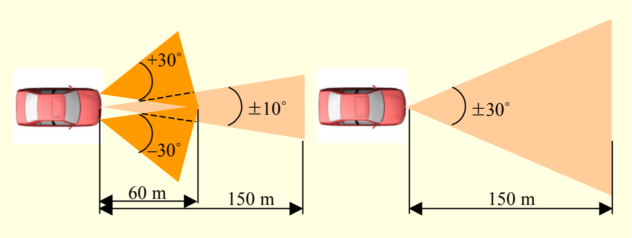

Fig. 1. Detection coverage of (a) general ACC stop-and-go radar system and (b) proposed ACC stop-and-go radar system.

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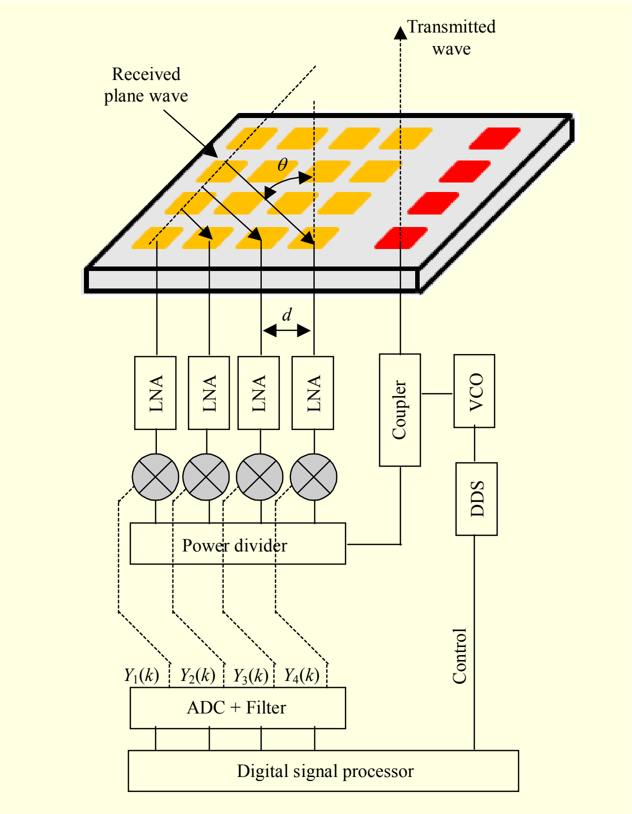


Fig. 2. System architecture of proposed radar.

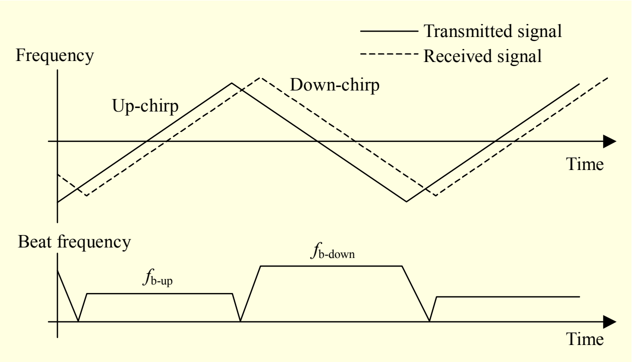


Fig. 3. FMCW modulation of proposed radar.

patch array antenna, GaAs RF ICs (for example, a voltage controlled amplifier (VCO), 4 low-noise amplifiers (LNAs), and 4 mixers), and a direct digital synthesizer (DDS), which can control waveform with high linearity and low-phase-noise.

The back-end module consists of a high-speed digital signal processor (DSP) for the calculation of the radar signal processing algorithm.

In order to extract the velocity and range information from the reflected target signal, we used the frequency modulated continuous wave (FMCW) modulation as shown in Fig. 3 [6]. Its center frequency is 24.15 GHz. The frequency sweep bandwidth is 200 MHz within the ISM band and chirp period is 3 ms. When the reflected received signals are mixed with transmitted signals, the beat signals are given by $f_{\text{b-up}} = |f_{\text{r}} - f_{\text{d}}|$ and $f_{\text{b-down}} = |f_{\text{r}} + f_{\text{d}}|$, where f_r is the range Doppler frequency and f_d is velocity Doppler frequency. Accordingly, the relative range and velocity of the target can be calculated by $R = [f_{\text{r}} \times c \times T]/2B$ and $V = [f_{\text{d}} \times \lambda]/2$, where c is the velocity of light, T is the period of each chirp, B is the transmitted bandwidth, and λ is wave length.

In order to extract exact angle detection with high resolution, compared to conventional beam forming [7], we designed the subspace-based digital-beam-forming algorithm with multiple signal classification (MUSIC) [8]. The signal model in the proposed array radar is defined by

$$Y(k) = A(\theta)s(k) + n(k), \tag{1}$$

where $A(\theta) = [a(\theta_1), a(\theta_2), \ldots, a(\theta_m)]$, $a(\theta)$ is a steering angle vector, m is the number of the target signal source, $s(k)$ is a desired signal, $Y(k)$ is the received baseband signal as shown in Fig. 2, and $n(k)$ is additive noise signal. The interval d between each receiver antenna is uniform at 0.5λ to achieve wide angle detection of more than ±30° by reducing the grating lobe during the angle steering. In the next step, the estimated covariance matrix of 4 received signals should be obtained by

$$\hat{\mathbf{R}} = \frac{1}{N}\sum_{k=1}^{N} Y(k)Y^H(k), \tag{2}$$

where $Y(k) = [Y_1(k)Y_2(k)Y_3(k)Y_4(k)]$. Then, the eigen decomposition of the covariance matrix **R**, which consists of signal and noise subspaces, can be performed as

$$\hat{\mathbf{R}} = APA^H + \sigma^2 I = U_{\text{s}}\Lambda_{\text{s}}U_{\text{s}}^H + \sigma^2 U_{\text{n}}U_{\text{n}}^H, \tag{3}$$

where $U_{\text{n}}^H a(\theta) = 0$, U_{s} and Λ_{s} denote an eigenvector and an eigenvalue of the signal source, respectively, and U_{n} is a noise eigenvector. Lastly, the spatial spectrum of the MUSIC algorithm is obtained by

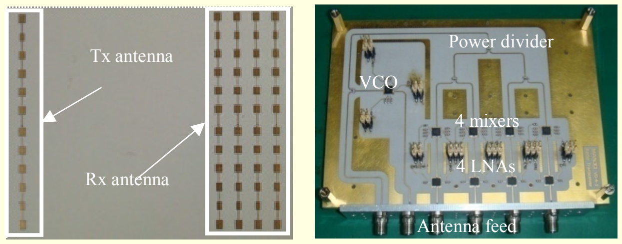
$$\hat{\mathbf{P}}_{\text{MUSIC}}(\theta) = \frac{\mathbf{a}^H(\theta)\cdot\mathbf{a}(\theta)}{\mathbf{a}^H(\theta)\cdot U_{\text{n}}\cdot U_{\text{n}}^H\cdot\mathbf{a}(\theta)}. \tag{4}$$

The direction of arrival from reflected target signals can be estimated by searching the peak of $\hat{\mathbf{P}}_{\text{MUSIC}}$.

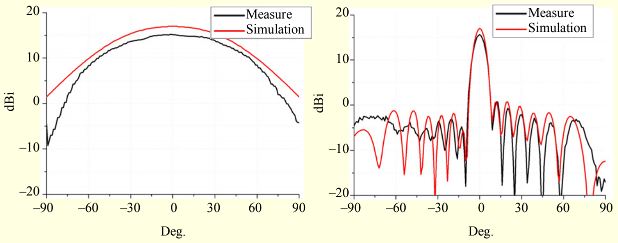
III. Design Results of the Proposed Radar

Figure 4 shows the design results with the cover of the proposed radar removed. The developed radar has a highly integrated size as shown in Fig. 4(f).

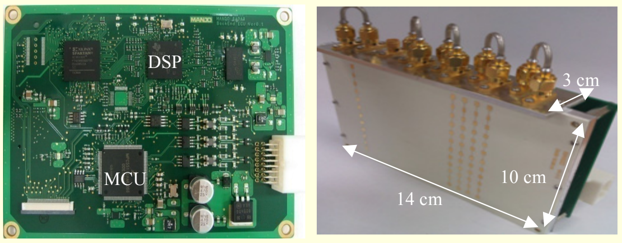
The design result of the patch array antenna is shown in



(a) Antenna (b) Transceiver



(c) Azimuth pattern (d) Elevation pattern



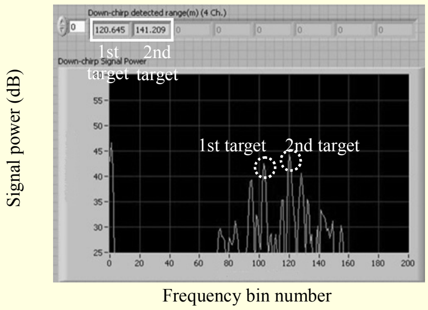
(e) Back-end module (f) Radar sensor

Fig. 4. Design results of proposed 24 GHz radar.

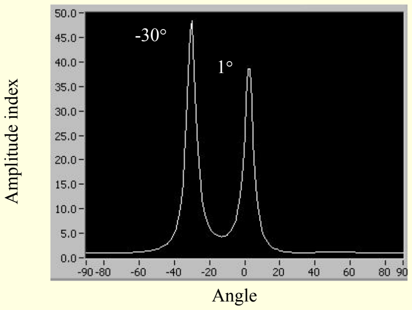
Fig. 4(a). All of the antennas consist of the same one-port linear array. The simulation and measurement results of the one-port linear array are shown in Figs. 4(c) and (d). The measured gain is 15 dBi and the half-power beam width is more than ±40° in the azimuth pattern. The side lobe level is 15 dB in the elevation pattern.

Figure 4(b) shows the design result of a transceiver that consists of an antenna feed, a power divider, and GaAs ICs (for example, VCO, 4 LNAs, and 4 mixers). The measured output power of VCO varies from 3.5 dBm to 4.5 dBm and the phase noise is –93 dBc/Hz at 100 kHz offset. The return loss of LNA is –15 dB and the noise figure is 3 dB. The gain is 26 dB at 24 GHz. The local oscillator (LO) return loss of mixer is –11 dB and LO/RF isolation is –32 dB. The return loss of power divider is –20 dB.

Finally, a back-end processing module is shown in Fig. 4(e). The DSP performs the coherent waveform control, 1024 FFT processing for beat signals, 10^{-6} false alarm rate and peak search processing for range and velocity detection, and MUSIC processing for angle detection with high resolution. The micro controller unit is used to communicate with vehicle sensors to control the brake and engine systems.



(a) Range detection



(b) Angle detection

Fig. 5. Experimental results of proposed 24 GHz radar.

IV. Experimental Results

All of the experiments were performed in an open space on flat dry ground at 25˚C. At 10 dBsm and 20 dBsm, which is the radar cross section (RCS) value, corner reflectors were used as targets for the detection test. Generally, a 10 dBsm corner reflector has almost the same RCS as a passenger vehicle, and a 20 dBsm corner reflector has that of large sedan.

Figure 5(a) shows that the detected range values of two targets, which were located at the range of 120 m and 140 m in the center lane, were 120.645 m and 141.209 m. The reflected power of two targets was measured as 43 dB and 45 dB, respectively. The power of the targets is higher than the noise and clutter around targets. The two targets, which were located at long range, could be detected by using a high gain antenna, GaAs RF ICs with low-noise figure and high gain, equalizer for the enhancement of baseband gain, and FFT gain compression.

In the next experimental result, Fig. 5(b) shows that the detected angle values of two targets, which were located at the same range of 20 m and different angles of +1° and –30˚, were exactly +1° and –30˚. The two targets could be sharply separated by using the MUSIC estimator. The minimal angle separation was 20° at the minimum 10 dB SNR.

V. Conclusion

In this letter, we proposed a cost-effective 24 GHz radar with high-resolution DBF and demonstrated that the proposed radar offers a detection capability for an ACC stop-and-go system as a single sensor. The predicted unit's annual cost for 100,000 volumes is under five hundred dollars.

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