76-GHz High-Resolution Radar for Autonomous Driving Support

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The development of autonomous driving has increased expectations for advanced ITS technology. To prevent traffic accidents at intersections in Japan, for example, roadside radio units transmit information about oncoming vehicles detected by roadside sensors to vehicles waiting to turn right on the opposing side. This paper describes the prototype of a 76-GHz band radar applicable as a roadside sensor. The radar adopts a multiple-frequency-stepped CPC (complementary phase coded) modulation method characterized by long-range detection without resolution degradation. The performance of this radar was verified in a field experiment.

Keywords: ITS, vehicle infrastructure integration system, millimeter wave radar, autonomous driving

1. Introduction

The recent growing interest in vehicle safety has prompted research and development to commercialize driving safety support and autonomous driving systems. The Japanese government has set the goal of reducing the number of traffic fatalities to below 2,500 by 2020. To meet this goal, the vehicle infrastructure integration system,*1 which enables information exchange between vehicles and infrastructure equipment by utilizing intelligent transport system (ITS)*2 technology, is necessary and field tests and other projects have been implemented through collaboration between the public and private sectors.

Figure 1 shows an example of the vehicle infrastructure integration system (driving safety support system) installed in Japan. A roadside sensor detects the position and speed of oncoming vehicles that will enter the intersection. The information is provided through the road-to-vehicle communication to the driver of the vehicle that will turn to the right, making it possible to recognize the oncoming vehicles that cannot be easily detected by the driver or in-vehicle sensors. Thus, this system helps prevent collisions when turning to the right.

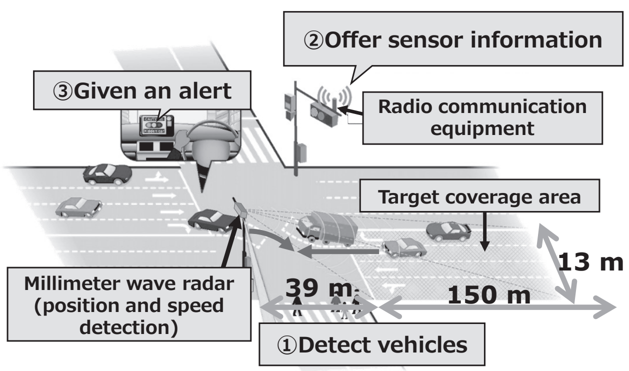

Fig. 1. Example of the vehicle infrastructure integration system (driving safety support system)

The roadside sensors used in the vehicle infrastructure integration system needs to ensure accurate detection of the vehicle position. Therefore, radar technology using radio waves that are unlikely to be affected by the time of the day and weather has attracted significant attention. High-resolution performance is required to detect multiple vehicles over a long range (150 m or more) and wide area (multiple lanes). In terms of radar performance, there is a trade-off between long-range coverage and high resolution, and it is difficult to attain both.

We undertook an R&D project from the Japanese Ministry of Internal Affairs and Communications in collaboration with the University of Electro-Communications from FY2014 to FY2016, and developed a 76-GHz band millimeter wave radar[(1)] that achieve both long-range coverage and high resolution. The performance was demonstrated based on an experiment using actual equipment to simulate the vehicle infrastructure integration system.

2. Mechanism of the Millimeter Wave Radar

The mechanism of the millimeter wave radar is explained using a pulse radar system as an example. Pulsed millimeter waves with high rectilinearity are transmitted. The time until the radio waves were reflected by an object and received (round trip time) is used to measure the distance to the object. In the case of a moving object, the frequency of the reflected waves is different from that of the transmitted waves due to the Doppler effect.*3 The speed can be calculated based on the frequency difference. To increase the resolution, the transmission pulse width must be narrowed, but the narrowed pulse width results in an expanded band, which requires expansion of the reception bandwidth. This increases noise and decreases the long-range coverage.

In this study, we used stepped-multiple-frequency CPC (complementary phase coded) modulation[(2)] as proposed by the University of Electro-Communications to solve the problem. Pulses are transmitted while stepping the frequency to expand the transmission bandwidth and attain high resolution, helping maintain the reception bandwidth and ensure long-range coverage. Thus, this sophisticated modulation can attain both long-range coverage and high resolution. The sequence of stepped-multiple-frequency CPC modulation is shown in Fig. 2.

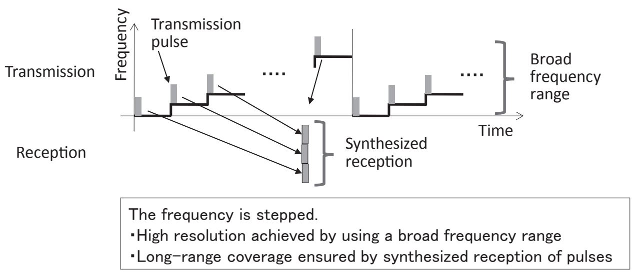

Fig. 2. Sequence of stepped-multiple-frequency CPC modulation

Two types of pulse waves are modulated based on the CPC*[4] strings for transmission. These waves are reflected by a detected object and subject to correlation processing and summation. This improves the signal-to-noise (S/N) ratio and suppresses noise that is generated otherwise (unnecessary signals in the distance direction), helping further increase the long-range coverage and resolution.

3. Configuration of the 76-GHz Band Millimeter Wave Radar

Figure 3 shows the functional block of the millimeter wave radar. The following sections describe the characteristics of each component that makes up the radar module: an antenna, 76-GHz circuit, and baseband circuit.

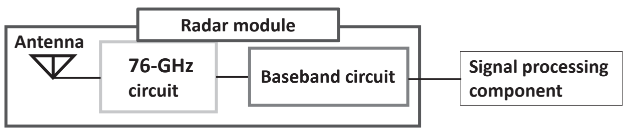

Fig. 3. Block diagram of the 76-GHz band millimeter wave radar function

3-1 Antenna

The reception S/N ratio needs to be increased to achieve long-range coverage and high resolution. This requires a high-gain antenna.

The driving safety support system will require a coverage area equivalent to four lanes by 150 m.[3] A wide directivity antenna is required. To meet these requirements, we improved the antenna design and developed a high-gain waveguide slot antenna with directivity for the required coverage area. The performance of the developed antenna is shown in Table 1.

Table 1. Performance measurement results for the transmission antenna

Item	Measurement value
Horizontal plane beam width	20°
Vertical plane beam width	8°
Gain	23 dBi

3-2 76-GHz circuit

To achieve a high S/N ratio, we developed a 76-GHz band radio frequency device that mainly consists of a high-gain and low-noise transmission and reception amplifier and a frequency converter, using gallium arsenide (GaAs). The details are described in “RF Module for High-Resolution Infrastructure Radars” in this issue. Specifically, the low-noise amplifier for the receiver achieves a gain of 30 dB and noise figure (NF) of 5 dB or less at the high frequency of 76 GHz (see Table 2).

Table 2. NF and gain of the low-noise amplifier

Low-noise amplifier for the receiver	Measurement value
Gain	30 dB
Noise figure (NF)	5 dB

3-3 Baseband*[5] circuit (frequency step function)

The stepped multiple frequency CPC modulation requires high-speed frequency switching. A switching mechanism achieved by simply configuring multiple transmission circuits in parallel would increase the circuit size and result in higher costs. Thus, we developed a proprietary compact and inexpensive baseband circuit using a synthesizer capable of high-speed switching.

Figure 4 shows the frequency changes of signals transmitted from the prototype baseband circuit. As indicated in the figure, the frequency is stepped quickly.

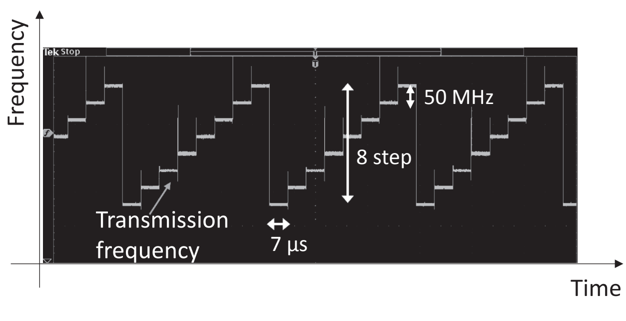

Fig. 4. Changes in the transmission frequency

3-4 76-GHz band radar module

The appearance of the 76-GHz band radar module is shown in Fig. 5. The prototype radar module obtained the technical regulations conformity certification required for outdoor experiments in accordance with the technical standards.[4]

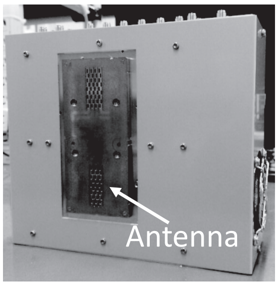

Fig. 5. Appearance of the radar module

4. Experiment to Verify Basic Performance

The 76-GHz band radar module was connected with the signal processing system at the University of Electro-Communications to conduct an experiment for verifying the resolution and long-range coverage.

4-1 Resolution

To evaluate the resolution, we conducted an experiment to detect two separate reflectors. The distance between the two reflectors was set to 34 cm, which is equivalent to the theoretical resolution limit calculated by the effective transmission bandwidth of the radar (430 MHz). Figure 6 shows the conceptual image of the experiment and measurement results. Two distinct peaks are indicated about 34 cm away from one another in the reflector installation distance. The measurement results show that the two reflectors are detected separately.

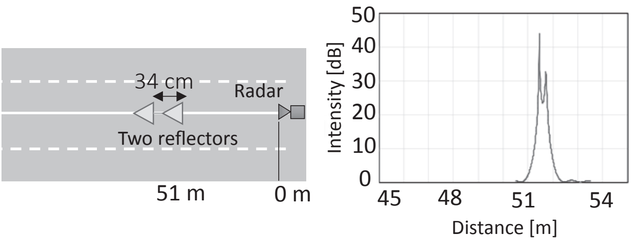

Fig. 6. Conceptual image of the experiment and measurement results

4-2 Long-range coverage

To investigate the vehicle detection capability within the target coverage area (see Fig. 1), a reflector with a radar reflection cross section of 10 dBsm was set up to simulate the vehicle reflection at two points (near end: 39 m, far end: 189 m) on the leftmost lane and measure the S/N ratio. The conceptual image and results of the experiment are shown in Fig. 7. The results showed a margin of about 10 dB even at the far end (189 m) compared to the required S/N ratio of 10 dB.

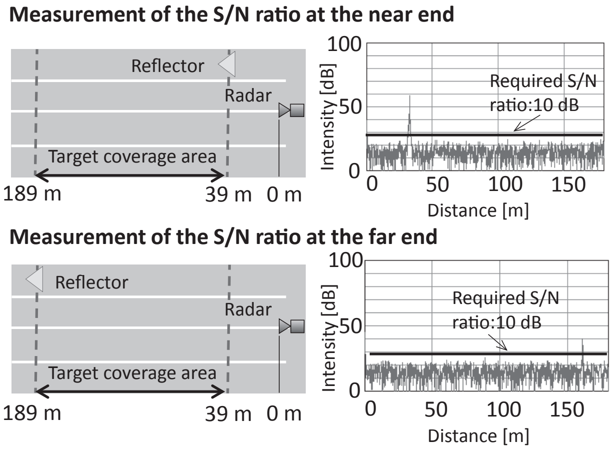

Fig. 7. Conceptual image of the experiment and measurement results

5. Vehicle Detection Experiment

Actual vehicle detection performance was verified at the Shirosato Test Course of the Japan Automobile Research Institute (JARI) and on a public road in Amagasaki City, Hyogo Prefecture. In the vehicle detection experiment, the 76-GHz band radar module was connected to our PC for processing signals to analyze the detection results.

5-1 Experiment on the test course

A 76-GHz band radar was set up at a height of six meters (based on the assumption that the radar will be set up on a signal post when put to practical use, see Fig. 8) at the Shirosato Test Course of JARI.

Two vehicles were driven in various patterns (e.g., in a row, side by side, overtaking). The results of two examples are presented below.

Fig. 8. Experiment on the test course

(1) Experiment to detect two vehicles in a row

An experiment was conducted to detect two vehicles cruising toward the radar while keeping a certain distance between them in the same lane.

Figure 9 shows two vehicles cruising in a row. It is difficult for the radar to separately detect two vehicles that are cruising with a certain distance kept between them in the same lane because their speed and angle are identical. The detection results (distance, speed, and angle) are presented in Fig. 10. The speed and angle detection results for the two vehicles are identical and overlap in the graphs. The two vehicles cannot be separately detected. The distance detection results show two vehicles with a certain distance from each other at a distance of between 200 m and 0 m (about 30 s to 50 s in time). The two vehicles are detected separately.

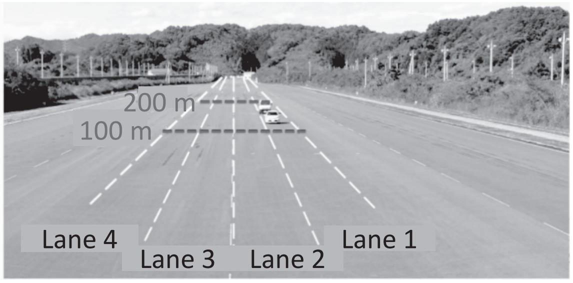

Fig. 9. Experiment to detect vehicles cruising in a row

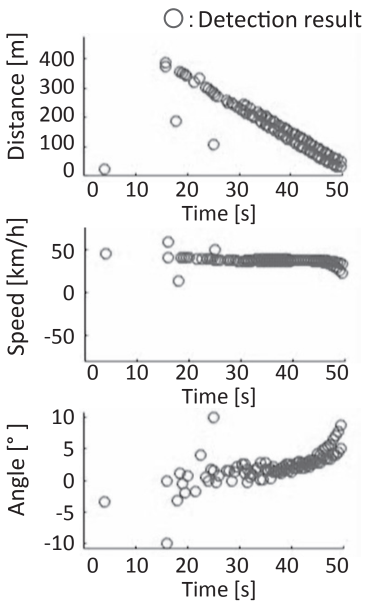

Fig. 10. Results of an experiment to detect vehicles cruising in a row

(2) Experiment to detect two vehicles side by side

An experiment was conducted to detect two vehicles cruising toward the radar side by side in two adjacent lanes.

Figure 11 shows two vehicles cruising side by side. It is extremely difficult for the radar to separately detect two vehicles cruising side by side in two adjacent lanes because their distance, speed, and angle are almost identical. The detection position was plotted on the distance matrix in Fig. 12 (the road seen from above, with the radar as the origin). The radar distinguishes vehicles cruising in Lanes 2 and 3 at a distance of 100 m or less. It should be noted that many points are plotted across the lanes at a distance of over 100 m. It is difficult to determine the lanes in which vehicles are cruising.

The detection results were then compensated using the Kalman filter*[6] to clearly separate vehicles cruising side by side. The compensated results are shown in Fig. 13.

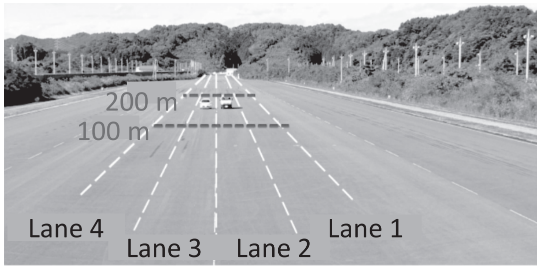

Fig. 11. Experiment to detect vehicles cruising side by side

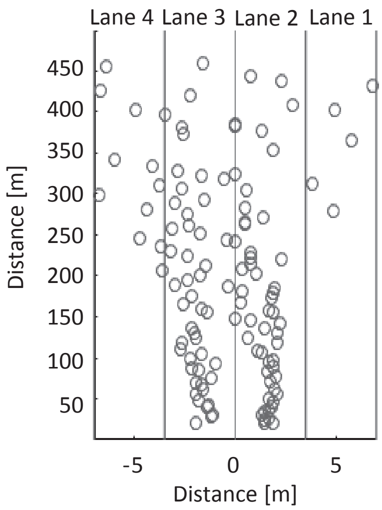

Fig. 12. Measurement results for vehicles cruising side by side (without a filtering process)

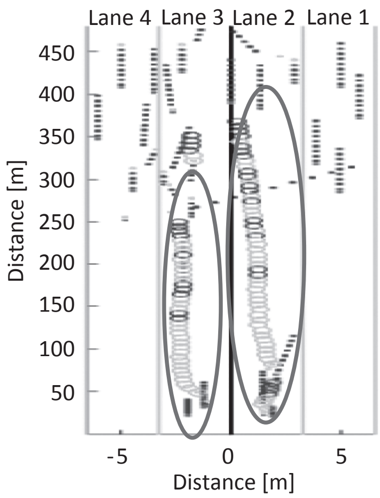

Fig. 13. Measurement results for vehicles cruising side by side (with a filtering process)

The results obtained by the filtering process clearly indicated that vehicles are cruising side by side in Lanes 2 and 3 in the 150 m section (distance: 39 m to 189 m).

5-2 Experiment on a public road

A vehicle detection experiment was conducted on a public road in Amagasaki City. The radar was set up on a footbridge (see Fig. 14). Figure 15 shows the radar detection results (square frames) superimposed on the camera image during the experiment. The dotted line frame represents the detection area (39 m to 189 m from the radar). Various vehicles are separately detected in a complicated situation where 10 or more vehicles are cruising in the detection area. The results show that vehicles are detected properly, although they overlap on the image captured by the camera and cannot be readily distinguished by the naked eye.

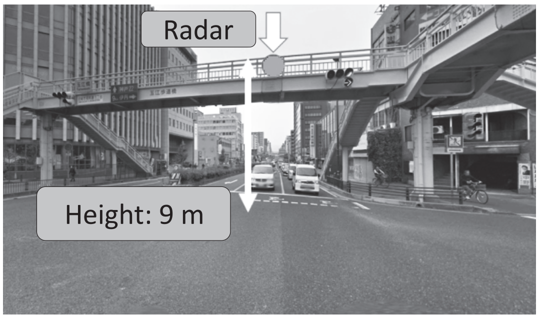

Fig. 14. Radars set up on a footbridge in Amagasaki City (conceptual image)

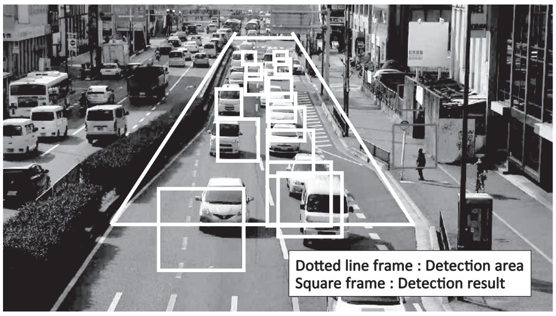

Fig. 15. Actual traffic flow in Amagasaki City and detection results

6. Conclusion

We developed a 76-GHz band roadside radar for assisting autonomous driving, and verified that both a resolution of 34 cm and long-range coverage of 189 m can be attained. We also verified that 10 or more vehicles in two lanes (distance: 39 m to 189 m) can be separately detected in the actual traffic flow. We will conduct experiments and evaluations in various environments to put the radar to practical use, and will develop functions immune to interference by in-vehicle radars.

This paper constitutes part of the accomplishments in "R&D for Narrow-band and High-Resolution Small Radar Technology for Both Near and Far Fields" in "R&D for Expansion of Radio Wave Resources" under the auspices of the Japanese Ministry of Internal Affairs and Communications (FY2014 to FY2016).

Technical Terms

*1 Vehicle infrastructure integration system: A system that enables information exchange between the traffic infrastructure and vehicles by using ITS technology.

*2 Intelligent transport systems (ITS): A system that connect people, roadside infrastructure, and vehicles via a network using information and communication technology to solve road traffic issues such as traffic accidents and congestion.

*3 Doppler effect: A phenomenon in which the frequency of waves (e.g., radio waves, acoustic waves) reflected by a moving object changes depending on the speed of the moving object.

*4 Complementary phase coded (CPC) strings: Two mathematically complementary code strings are used for phase modulation in a pulse. Given that the strings are complementary, the side lobe can be reduced by summating the respective correlation results.

*5 Baseband: The frequency band of signals before modulation or after demodulation.

*6 Kalman filter: A linear filter to estimate or control the condition of a dynamic system using observed values that contain errors.

References

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