Effects to develop a high-performance millimeter-wave radar with RF CMOS technology

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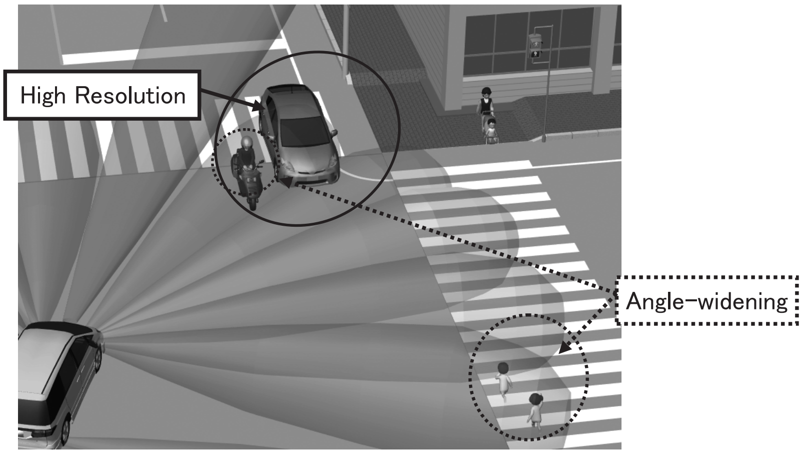

Abstract

We are aiming for the realization of a "Future Link™" for analyzing "unusual driving situations" and "possible events" by sensing traffic information, a pedestrian, an external environment of vehicles, a host vehicle, and a driving status. The sensors for the "Future Link™" need to detect the surrounding environment of the vehicle in all weathers accurately. Then we are developing the millimeter-wave radar focused on the RF CMOS(Complementary Metal Oxide Semiconductor) technology which can handle the millimeter-wave signal because of the enhancement of miniaturize process technology and the speed-up of its operational frequency. This paper reports the effects of achieving the highly distance resolution for detecting the adjacent targets such as vehicles and pedestrians separately and the wider FOV (Field of view) for detecting the all objects around the vehicle. We will contribute a vehicle society, which is the objective of the "Future Link™", by enhancing the performances of the millimeter-wave radar with the RF CMOS technology.

1 Introduction

FUJITSU TEN is aiming for realization of "Future Link™" service for analyzing "unusual driving situation" and "possible events" by sensing the traffic information, a pedestrian, the external environment, a host vehicle and the driving status and by combining the results. The use of "Future Link™", for example, makes it possible to provide a driver with the information that urges him/her to act promptly by looking ahead of traffic information and possibility of immediate danger to a driver. In order for a driver to look possible danger ahead, the surrounding environment of his/her vehicle needs to be detected accurately in all types of weather conditions by use of external sensors. We have commercialized a millimeter-wave radar as an external sensor capable of detecting a target object even under the poor visibility weather condition such as a fog and others [1]. However, the current millimeter-wave radar mainly detects the front vehicle of the host vehicle. In order for the millimeter-wave radar to detect the surrounding environment of a vehicle accurately, separated detection of the adjacent vehicle and the pedestrian with high-precision of distance resolution, and also detection with high functionalization, such as angle-widening for detecting all surroundings of the vehicle are essential.

The millimeter-wave radar mainly consists of the MMIC (Monolithic Microwave Integrated Circuit) circuit which transmits and receives the high frequency signal, the signal processing circuit and the control circuit. MMIC, especially, has a big impact on the performance and the cost of the millimeter-wave radar. Generally, the SiGe(Silicon Germanium) and the GaAs(Gallium Arsenide) semiconductor technologies have been used for a MMIC, because of its high frequency performance, however, they are high in cost. On the other hand, CMOS (Complementally Metal Oxide Semiconductor) technology, used for CPU and a memory, has been becoming able to handle millimeter-wave signals because of its advancement of refining technology that makes the operation performance very high in speed. In **Fig. 1** the frequency performance index Ft and Fmax which are the device indicator of the Si system process produced or developed for general use, and low-noise index NFmin are plotted together. [2]

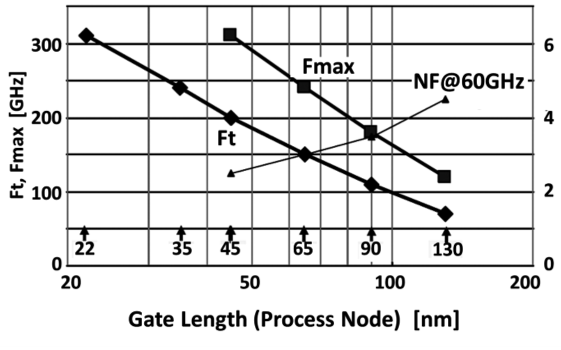

Fig.1 Device Performances of the Si-CMOS Process

Moreover, CMOS technology has better character such as low cost, low power consumption and compatibility with the digital circuit, and is also less expensive and more suitable for the integration than GaAs and SiGe technology.

We have focused on CMOS technology and enhanced the performance of the millimeter-wave radar. This paper reports our approach to angle-widening and resolution enhancement of the millimeter-wave radar.

2 Trend and Expectation of CMOS MMIC

MMIC for wireless communication system is a primary product of CMOS technology use device for mobile phone, wireless LAN and others which perform in relatively low frequency band and output power by improved performance of Si system device. Moreover, these CMOS technology have advanced not only in functional RF circuits, but also in system-on-chip which is constituted of modulation-demodulation part, baseband signal processing part and control circuit in one device. On the other hand, as for millimeter-wave band as well, enhancing the performance of RF part is ongoing by applying the latest process. The use of CMOS technology for Millimeter-wave band MMIC will also have possibility to be increasingly general for the application field to handle low power output as well as low frequency band in the future.

Fig. 2 shows block diagram of the millimeter- wave radar. The current millimeter-wave radar is composed of individual chips such as transceiver (TX) MMIC, receiver (RX) MMIC and control circuit. By applying CMOS technology which has high compatibility with digital circuit to this MMIC (**Fig. 2**: dotted line parts), it is possible to mount the each type of sensor such as a control circuit, a temperature sensor and etc. with MMIC together. Thereby it becomes possible to control the transceiver with high accuracy, for example by automatically self-correcting the output power and others. And also an improvement of the high frequency performance and a high functionalization can be expected.

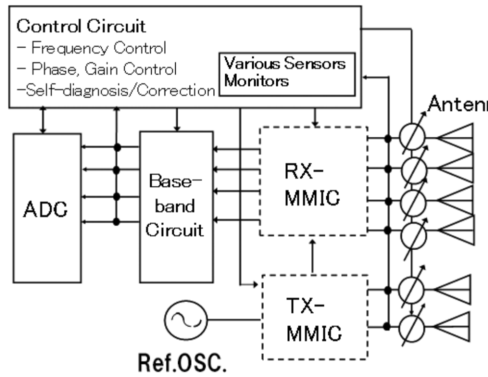

Fig.2 Block Diagram of the Millimeter-Wave Radar

3 Issues of Millimeter-Wave Radar with CMOS Technology

Table. 1 shows the result of the comparison of conventional semiconductor SiGe and GaAs technology with CMOS technology. CMOS technology is superior in high integration and also in energy consumption.

Developing MMIC by use of CMOS technology provides an expectation for high functionalization of the millimeter-wave radar, however, we are concerned whether its RF characteristics reach a practical level.

Moreover, there are only a few case reports of CMOS technology use millimeter-wave radar in the world.

Therefore, we decided to confirm the effectiveness of high functionalization by use of CMOS technology in following steps stated below.

In a Step1, we confirm the feasibility of advanced features by developing an element circuit with CMOS technology.

In a Step2, we develop a transceiver MMIC, and compare it with one by conventional semiconductor technology for SiGe and others. Then we confirm feasibility of it for MMIC.

Table 1 Comparisons of the Semiconductor Technology

	CMOS	SiGe	GaAs
Power Consumption	◎	○	△
Speed	◎	◎	◎
Output Power	○	◎	◎
Integration	◎	○	△
Cost	○	○	△

4 Efforts toward Advanced Features

4.1 CMOS Circuit Realizing Angle-Widening

As a Step1, we targeted angle-widening of detection range of the millimeter-wave radar and implemented circuit development by use of CMOS technology. This time, for realization of angle-widening of the millimeter-wave radar, we developed the circuit by use of APA (Active Phased Array) method. **Fig. 3** shows the configuration of the radar to which adapted transmission APA (Active Phased Array) method[6]. APA method enables beam narrowing and beam scanning with phase composing by use of phase shifter equipped to each transmission channel. As compared to DBF (Digital Beam Forming) method, which estimates the arrival direction by digitally processing the signal from antenna which has the wide directivity, APA method makes angle-widening possible by generating narrow-angle beam and scanning it so as to improve the gain per single beam.

Block diagram of the phase shifter and CMOS circuit which we developed this time is shown in **Fig. 4**[5] and the evaluation result of phase shifter (Configurable phase shifter range) according to DAC is shown in **Fig. 5**[7].

The phase shifter consists of one 90 degree hybrid, two single-input-differential-output amplifiers and four variable output gain amplifiers (VGA). The signal that has desired phase information can be obtained by vector resultant of two signals chosen after inputting four signals which have different phase in 90 degree each other to four VGAs. Each VGA is connected to a digital analog converter (DAC). These processes made it possible to set gate bias voltage and output voltage of two signals with high-precision. Furthermore, the result of evaluation in **Fig. 5** shows that the phase can be set with a wide range of 74GHz to 82GHz frequency band and with the entire range of phase up to ±180 degree, and excellent linearity. This makes possible phase control with high precision and beam scanning with APA method.

Configuration of phase difference/amplitude difference detection mixer is shown in **Fig. 6**. Phase difference/amplitude difference detection mixer is a circuit which is equipped between transmitting or receiving channels and makes it possible to detect the amount of the gap of phase/amplitude between the channels. This circuit consists of two mixers and delay circuits. Depending on phase difference of the input signal as shown in **Fig. 6**, voltage V_A and V_B are output to each A and B of these circuits. The sum and difference of these voltages are shown in **Fig. 7**. The maximum sensitivity value of voltages of sum and difference are at 0 degree, +90 degree, 180 degree and -90 degree. Then the smallest value of phase error is shown by the oval shaped part in **Fig. 7**. By selecting the oval shaped part as the smallest value of phase error (selecting either sum or difference of voltage), we confirmed the phase different detection with high accuracy and the detection error was equal to or less than 3 degree. (**Fig. 8**).

These CMOS circuits enable APA method adoption as shown in **Fig. 3**, and realization of widening the millimeter-wave radar detection range. Moreover, by mounting these CMOS circuit with logic circuit for controlling together, it is possible to detect the phases of each channel signal with high precision and perform correction instantly, thus further high functionalization of APA method can be expected.

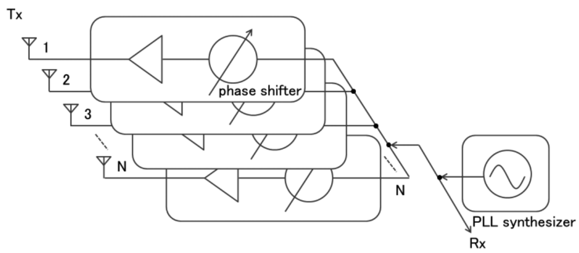

Fig.3 Configuration of the Tx APA Radar

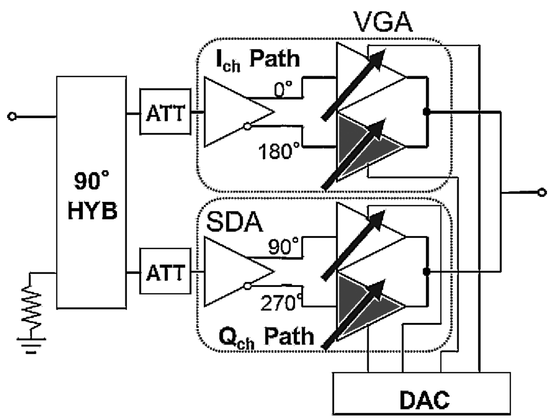

Fig.4 Block Diagram of the Phase Shifter Using a Vector Combining Technique

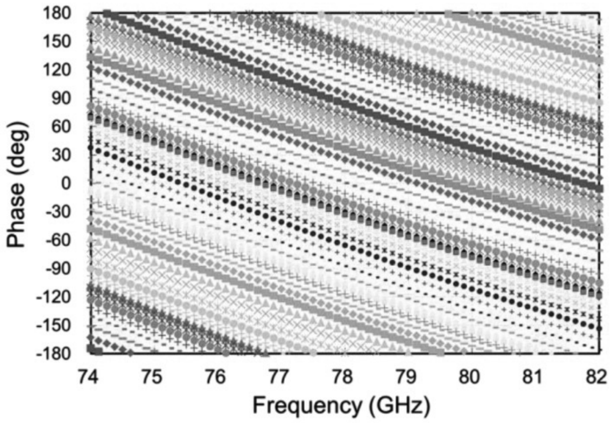

Fig.5 Measured Phase Variation of the Phase Shifter (Configurable Phase Shifter Range)

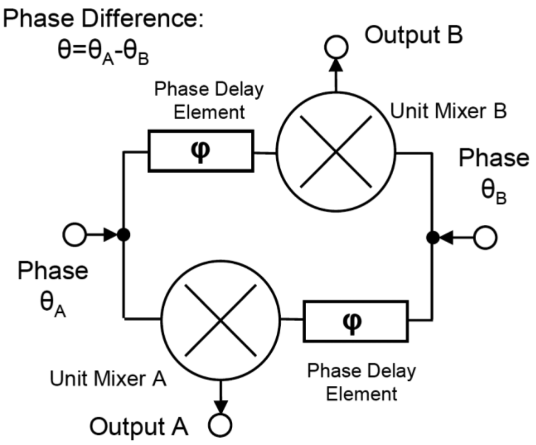

Fig.6 Configuration of the Phase and Power Difference Detection Mixer

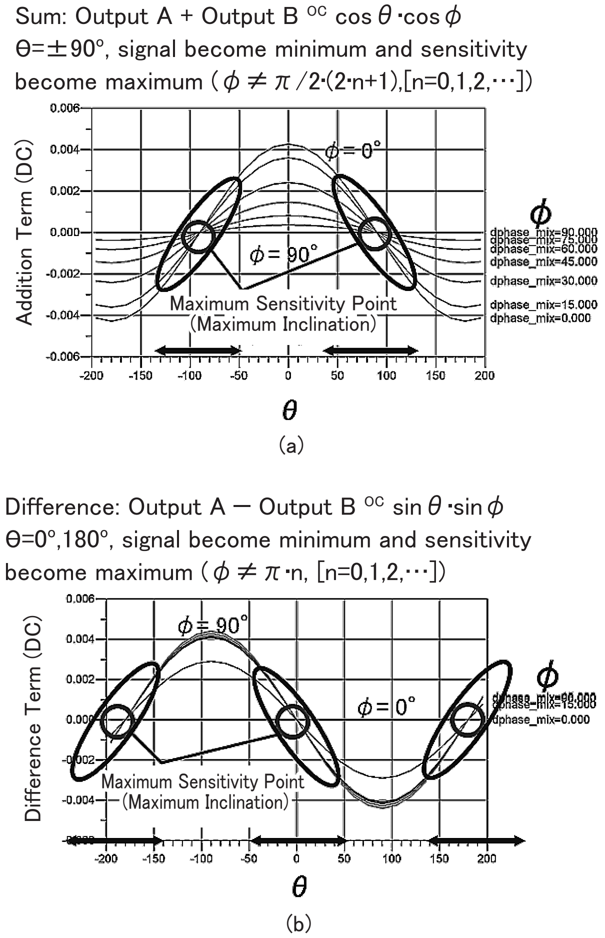

Fig.7 Measured and Calculated Outputs of the Phase Difference Detection Mixer

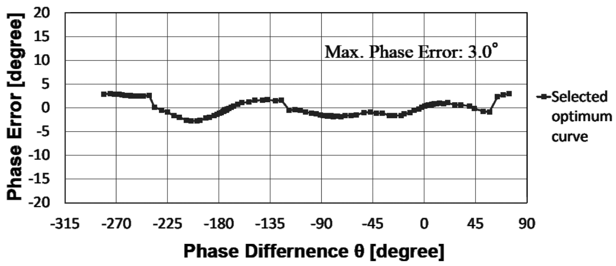

Fig.8 Measured Phase Difference Detection Performance

4.2 CMOS Transceiver MMIC

As a Step 2, we developed a transceiver MMIC for our radar by use of CMOS technology. It consisted of Tx MMIC as a transmitter and Rx MMIC as a receiver in line with the specification of our conventional SiGe transceiver.

The block diagram of developed Tx MMIC and Rx MMIC are shown in **Fig. 9** and **Fig. 10** respectively. The image of MMIC is shown in **Fig. 11** [3]. Tx MMIC enabled multichannel output (Tx1、Tx2), and consisted of power amplifier (PA), drive amplifier (DA), phase locked loop circuit (PLL) for signal generation and Local part. Rx MMIC was capable of multichannel input (Rx1 to Rx4), and consisted of low-noise amplifier (LNA), DA and mixer (MIX).

Extraction of performance issues as MMIC was done by comparing the characteristics of MMIC which was developed by use of CMOS technology this time, with our conventional SiGe MMIC. **Table 2** shows the characteristics of CMOS MMIC. The results in **Table 2** shows that CMOS MMIC gains equivalent performance to the conventional SiGe. It was confirmed to be capable of applying CMOS technology to the millimeter-wave radar. And it was confirmed that the electric output power and the noise charactaristic also had sufficient results as MMIC for the millimeter-wave radar.

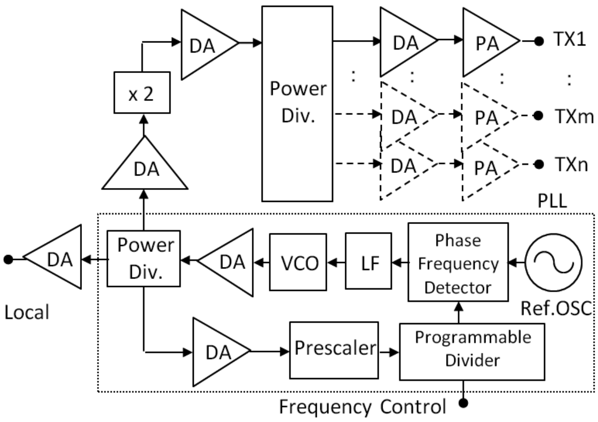

Fig.9 Block Diagram of the Tx MMIC

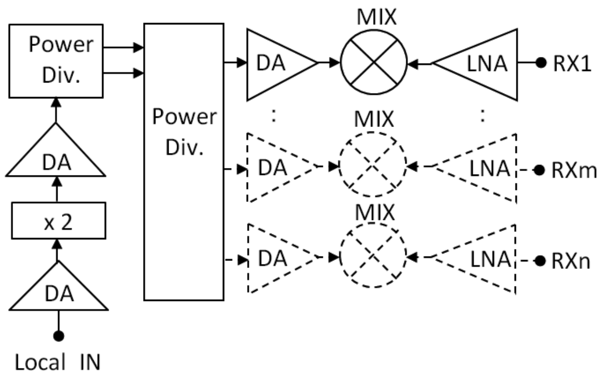

Fig.10 Block Diagram of the Rx MMIC

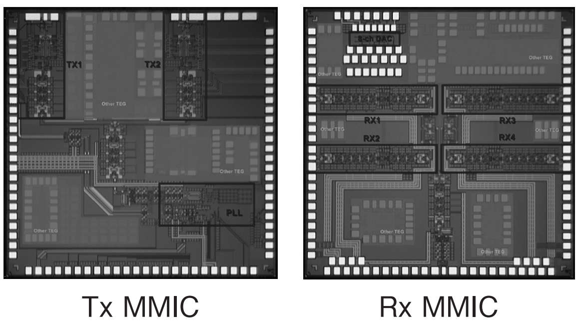

Fig.11 Developed Transceiver MMIC (4.1×4.1mm[2])

Table 2 Characteristics of the CMOS MMIC

Tx	Frequency	(GHz)	76-81
	Output Power	(dBm)	10
	Phase Noise	(dBc/Hz)	-84
	Power Consumption	(W)	0.75
Rx	Frequency	(GHz)	76-81
	Conversion Gain	(dB)	20
	Noise Figure @100kHz offset	(dB)	12
	Power Consumption	(W)	0.5

4.3 Approach to Resolution Enhancement by Use of CMOS Technology

Evaluation of resolution enhancement was performed by use of CMOS Tx MMIC and Rx MMIC which developed in the step2.

The performance of distance resolution of a millimeter-wave radar is determined by the modualtion system. There are some systems for the modulatin system, for example, FMCW (Frequency Modulated Continius Wave) system, puls system and etc. Depending on the selection from these systems, some specifications, such as detection method for the distance and relative speed, performance to be obtained and system configuration change accordingly.

MMIC which we developed this time is compatible with FMCW system on which we have enough performance. The distance resolution ⊿R of a millimeter-wave radar on FMCW system is represented as following mathematical formula.

$$\Delta R = A\frac{c}{2\Delta F}$$

This formula represents the coefficient of speed of light as c and modulation frequency bandwidth as ⊿F. And A represents the coefficient related to the window function and influence of the signal processing and so on, which are factors that deteriorate the distance resolution. Then, the wider width ⊿F is, the higher the resolution become. The frequency modulation band of Tx MMIC which produced experimentally this time is capable of processing 78 to 81GHz band, including conventional 76 to 77GHz band to adapt it to broadband modulation method that realizes high resolution. On this occasion, we adapted it not only to RF circuit but also to high resolution by controlling and tuning high-speed digital circuit [4]. The transient characteristics of Tx MMIC are shown in **Fig. 12**. From this result, it was confirmed that the high resolution method can be applied because the frequency sweeps linearly even if modulation band width increases to broadband. **Fig. 13** shows the transmission spectrum when its center frequency is 79GHz, and its modulation bandwidth is 3GHz. It was confirmed from the result that desired transmission spectrum is obtained even in the case of sending out modulated signal with 3GHz which means broadband.

We assembled this MMIC as a transceiver and evaluated this. We set up a target (corner reflector) around

30m of distance and measured distance resolution with the beat frequency signal received from the reflection of two adjacent targets. Then we measured distance resolution by setting 480MHz and 3GHz as modulation band width to confirm distance resolution improving effect when high resolution method was adopted. The result of the measurement is shown in **Fig. 14**. When the modulation band width was set to 480MHz (**Fig. 14-1**), two targets of which distance was around ⊿R = 1.2m were able to be separated, but on the other hand, when the high resolution method was used (**Fig. 14-2**), they were separated of which distance was even around ⊿R = 0.2m. It was confirmed from this result that the high frequency resolution performed by CMOS technology makes it possible to separately detect, for example, a vehicle and a pedestrian, and pedestrians close each other.

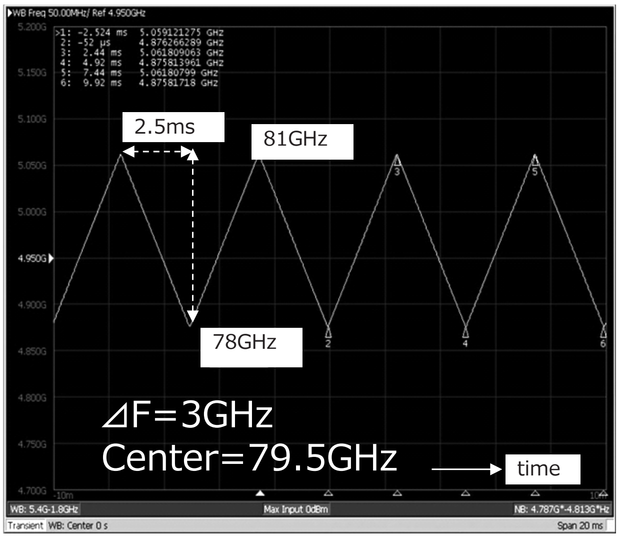

Fig.12 Measured Transient Response of the Transmitter

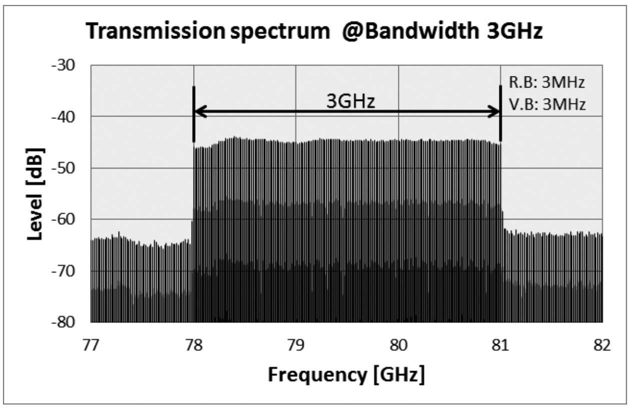

Fig.13 Measured Transmission Spectrum at 3GHz of Modulation Bandwidth

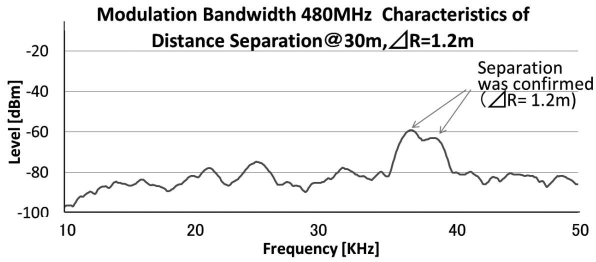

Fig.14-1 Characteristics of Distance Separation (⊿R=1.2m, Modulation Bandwidth 480MHz)

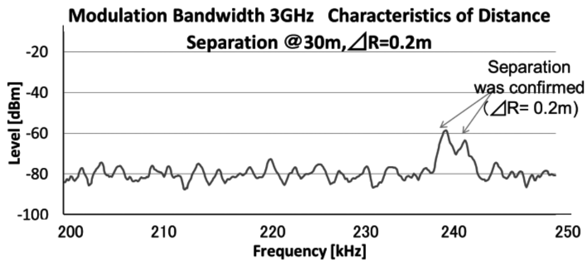

Fig.14-2 Characteristics of Distance Separation (⊿R=0.2m, Modulation Bandwidth 3GHz)

5 Summary of Enhancing Performance by Using CMOS Technology

In order to enhance the performance of the millimeter-wave radar, we confirmed the following details by focusing on CMOS technology and implementing the development of MMIC and CMOS circuit.

①We developed transceiver MMIC by use of CMOS technology. As a result, we confirmed that the MMIC characteristics with CMOS technology was obtained, which was close to one of conventional MMIC using SiGe and etc.

②We developed and evaluated CMOS MMIC which was capable of the wide band modulation, and also a transceiver which installed it, and evaluated the transceiver. From the evaluation result, we confirmed the high frequency resolution method is realizable by use of CMOS technology.

③We produced a phase shifter and a phase difference detection mixer as CMOS circuit experimentally, and confirmed circuit operation thereof. From this result, we confirmed that the APA method is realizable by use of CMOS technology as one example of radar systems which realize angle-widening of the detection range.

We plan to confirm a feasibility of the radar capable of APA method by developing a transceiver MMIC which installed a CMOS circuit realizing angle-widening, and the radar which installed it in future.

6 Summary

This paper reports the effort for high functionalization of the millimeter-wave radar by use of CMOS technology. We will contribute to realization of vehicle society, which is the objective of "Future Link™", by continuous effort for enhancing the performance of the millimeter-wave radar with RF CMOS technology.

※Future Link™ is a registered trademark of FUJITSU TEN Limited.

※The proper nouns of product names and the like indicated in the paper are trademarks or registered trademarks of the respective companies.

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