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Implementation of an LFM-FSK Transceiver for Automotive Radar

HyunGi Yoo[1], MyoungYeol Park[2], YoungSu Kim[2], SangChul Ahn[2] and Franklin Bien[1*]

[1] School of Electrical and Computer Engineering, Ulsan National Institute of Science and Technology, Banyeon-ri, Eonyang-eup, Ulju-gun, Ulsan, Korea {bien}@unist.ac.kr
[2] Comotech corp. R&D center, 908-1 Apt-bldg, Hyomun dong, Buk-gu, Ulsan, Korea mypark@comotech.com

***** Corresponding Author: Franklin Bien

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** Short Paper*

Abstract**:** The first 77 GHz transceiver that applies a heterodyne structure–based linear frequency modulation–frequency shift keying (LFM-FSK) front-end module (FEM) is presented. An LFM-FSK waveform generator is proposed for the transceiver design to avoid ghost target detection in a multi-target environment. This FEM consists of three parts: a frequency synthesizer, a 77 GHz up/down converter, and a baseband block. The purpose of the FEM is to make an appropriate beat frequency, which will be the key to solving problems in the digital signal processor (DSP). This paper mainly focuses on the most challenging tasks, including generating and conveying the correct transmission waveform in the 77 GHz frequency band to the DSP. A synthesizer test confirmed that the developed module for the signal generator of the LFM-FSK can produce an adequate transmission signal. Additionally, a loop back test confirmed that the output frequency of this module works well. This development will contribute to future progress in integrating a radar module for multi-target detection. By using the LFM-FSK waveform method, this radar transceiver is expected to provide multi-target detection, in contrast to the existing method.

Keywords**:** 77-GHz radar module, Front-end module (FEM), LFM-FSK, Multi-target detection, Millimeter wave transceiver, Patch array antenna, RF, Homodyne structure

1. Introduction

An intelligent transportation system (ITS) is a representative fusion technology that brings vibrant change to the car itself by using information technology, such as smart cruise control and blind spot detection (BSD) [1-3]. Over the years, various attempts have been made to develop and adapt techniques to provide convenience [4-6]. Considering the potential for treacherous driving conditions, automotive assistance systems require a reliable tracking system. Thus, radar, which has been widely used in the military and aviation fields, has emerged as an alternative approach [7-9]. Today, car companies and suppliers are already working to develop the next-generation of long-range radar (LRR) at 77 GHz, which will improve the maximum and minimum ranges, provide a wider field of view, as well as improved range, angular resolution and accuracy, self-alignment, and blockage detection capability. The most commonly used LRR is the frequency-modulated continuous wave (FMCW) radar because of its high performance-to-cost (P/C) ratio compared to other radar modulation methods. However, this FMCW radar waveform has some serious limitations in multiple target situations due to the technically complicated association step. On the other hand, linear frequency modulation–frequency shift keying (LFM-FSK), which combines a frequency shift–keying method with a linear frequency modulation waveform, is seen as a new alternative in this situation because of its advanced structure [10, 11]. This paper presents a transceiver module for a 77 GHz complementary metal-oxide semiconductor long-range automotive radar module, which was developed to provide accurate information for consumers, even in multi-target situations, by using the LFM-FSK radar method. Section 2 identifies the overall architecture of this radar module, and Section 3 gives a system description, which is followed by a presentation of the measured results in Section 4. The conclusions are presented in Section 5, the final section of this paper.

2. Overall Architecture

2.1 LFM-FSK

In the automotive radar market, the classic radar module has some limitations due to its structure. The most common limitation is difficulty detecting multiple targets in real traffic environments. There have been a variety of solutions by developing an advanced module [12-14]. In this paper, the LFM-FSK radar front-end module (FEM) is proposed for a transceiver design to avoid ghost target detection in a multi-target environment. The LFM-FSK waveform is a new waveform designed for automotive applications, based on continuous wave (CW) transmit signals, which leads to an extremely short measurement time. The basic idea is a combination of LFM and FSK CW waveforms in an intertwined technique. Unambiguous range and velocity measurement with high resolution and accuracy can be required in this case, even in multi-target situations.

2.2 Overall Architecture

The main purpose of the radar module is gathering and supplying correct results to a user. As demonstrated in Fig. 1, the radar module commonly consists of three parts: an FEM, an antenna, and a digital signal processing (DSP) module. Among these, constructing an efficient radar FEM with the correct waveform generator was commonly considered to be the most challenging task. This is an FMCW signal waveform to which the classic frequency shift keying (FSK) modulation method has been applied. This module consists of the radar FEM, microstrip patch array antenna, up/down converter, baseband block, and DSP module. Every part is covered in this paper, except the DSP and antenna. To implement the LFM-FSK radar FEM, a heterodyne structure was considered, which is one of the most stable ways to generate a signal waveform using radar technology. In this structure, the signal was generated by the frequency synthesizer block though the phase locked loop (PLL) block with a crystal oscillator. The 77 GHz up/down converter down-converted the received signal, which was up-converted from the baseband block to 77 GHz in the transmission module before reaching the antenna array with an up-and-down mixer. The baseband block located after the converter handles the signal filtering process to efficiently supply information to the next module, the DSP. The hybrid coupler in the up/down converter is employed to supply this beat frequency by simultaneously distributing the generated signal to the transmit antenna and baseband block. In the LFM-FSK radar waveform method, the beat frequency needs to be calculated using special equations.

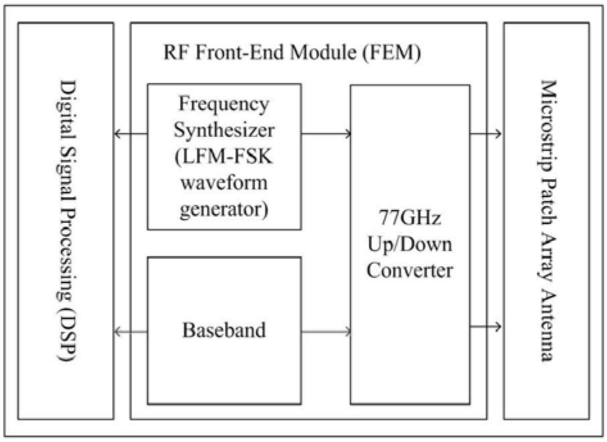
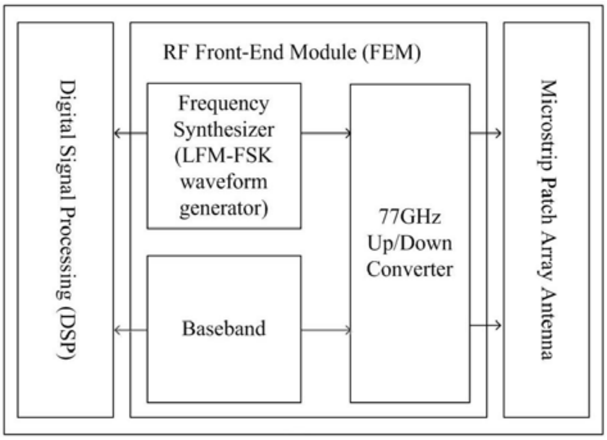
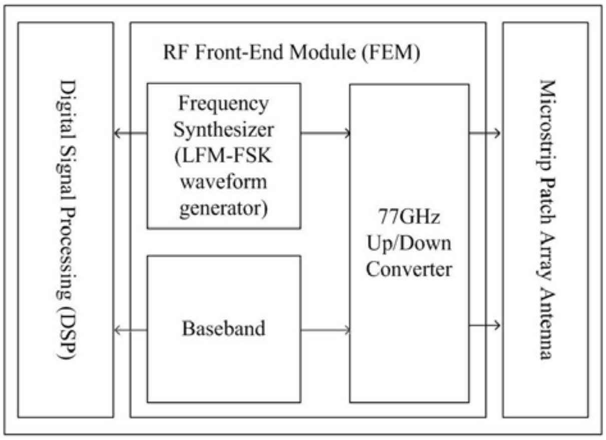


Fig. 1. 77 GHz LFM-FSK radar module.

As demonstrated in Fig. 2, there are key concepts that allow this module to be implemented successfully. First, the frequency range of the synthesizer is 76.5 to 76.6 GHz, with enough chirp time and delay time. Chirp time is the overall elapsed time in one period. The delay time mentioned here is the float time during which the DSP implements the algorithm, which gives the information to the user. This module also has the goal of generating a signal with enough fstep (the difference value between two transmitting signals). A crystal oscillator was employed in the synthesizer block to generate the signal. The receiver translates the channel of interest directly from 77 GHz to the baseband block in a single stage. This structure needs



(a) With f_{shift} / f_{step}



(b) With chirp / delay time

Fig. 2. LFM-FSK waveform.

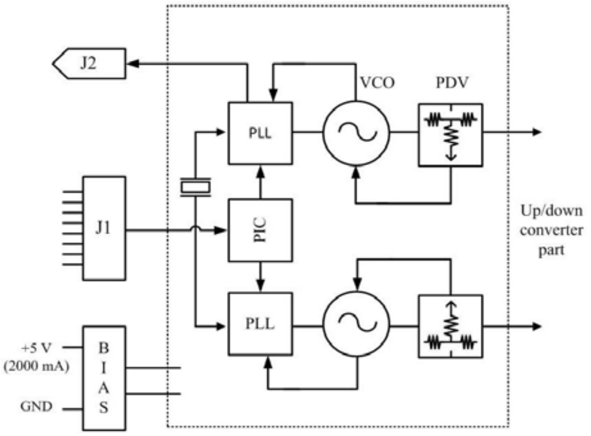


Fig. 3. Block diagram of the synthesizer.

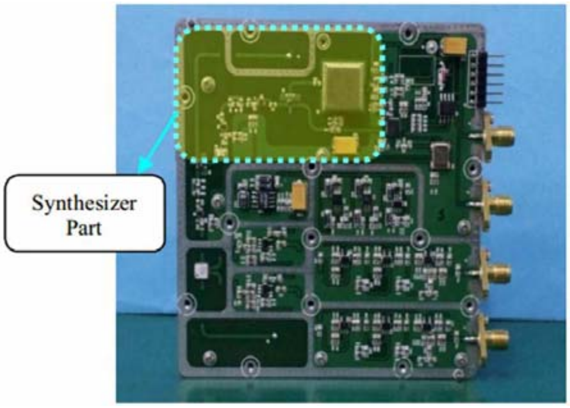


Fig. 4. Synthesizer of 77 GHz FEM.

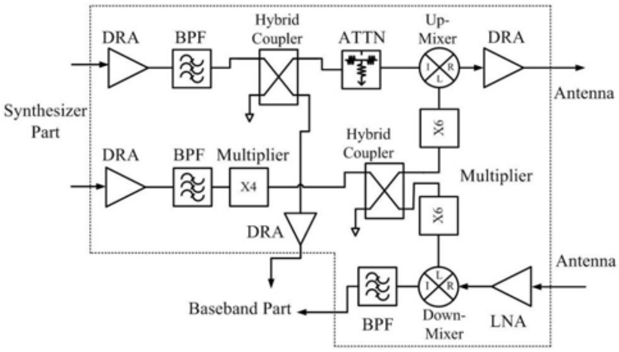


Fig. 5. Block diagram of a 77 GHz up/down converter.

less hardware compared to a heterodyne structure, which is currently the most widely used structure in wireless transceivers. In this structure, the integrated circuit's low noise amplifier (LNA) does not need to match 50 Ω because there is no image reject filter between the LNA and mixer. Another advantage of this structure is the amplification at the baseband block, which results in power savings.

3. System Description

3.1 Front-End Module (FEM)

The implemented radar module includes the synthesizer, 77 GHz up/down converter, and baseband block. Fig. 3 shows the implemented block synthesizer. The PLL in the radar FEM generates a baseband signal at 3 GHz. The 77 GHz up/down converter processes the generated signal passed from the frequency synthesizer block. In the transmit stage, this block converts the signal to the 77 GHz frequency band to radiate the RF signal, while the reflected signal from the target is down-converted in the receiver stage.

3.2 Synthesizer Block

As demonstrated in Fig. 3, this block is divided into the synthesizer, which generates the LFM-FSK waveform, and the PLL, which generates the local oscillator (LO) frequency, along with the power divider (PDV), which sends the phase information to the voltage-controlled oscillator (VCO) to generate the correct signal in the PLL. This module requires the signal to have an LFM-FSK shape for multi-target detection. In the synthesizer, the VCO generates a 3 GHz signal. The PLL creates a specialized shape waveform according to a command from the PIC block, which generates the programming code from the J1 outside the synthesizer block. The lock detector controls the generated signal through J2, which verifies the operation of the PLL.

The conventional PLL is a chip that is used for the purpose of locking a fixed frequency. On the other hand, this module uses a fractional synthesizer that locks the PLL by controlling the VCO. This module includes the VCO block in the synthesizer block to generate a stable waveform, while the primary design concept is ensuring immunity to noise when each frequency step is changed. Therefore, this synthesizer generates a variety of modulated waveforms, such as single, sawtooth, and triangular ramp. In particular, this structure can generate a waveform that has regular intervals and time delay. By using this, we can make a specialized ramp that is similar to the LFM-FSK waveform in transmission output. Here, the output frequency of the LO is 3 GHz with the VCO output frequency shift. Thus, we can generate a very similar LFM-FSK signal in the synthesizer block by using this PLL. The PDV element controls the VCO by comparing the phases of the two signals, which are the input signal and reference signal in the PLL. To operate this synthesizer block, this module uses a 5 v/2000 mA bias source, which comes from outside the module. Fig. 4 shows the implemented synthesizer of a 77 GHz FEM. This block can minimize the interference from another block's signal due to the metal wall.

3.3 77 GHz Up/down Converter Block & Baseband Block

As demonstrated in Fig. 5, the up/down converter consists of a transmitter and receiver pair, and the signal is raised to 77 GHz through the LO. After mixing with the carrier frequency in the receiver, there is a phase

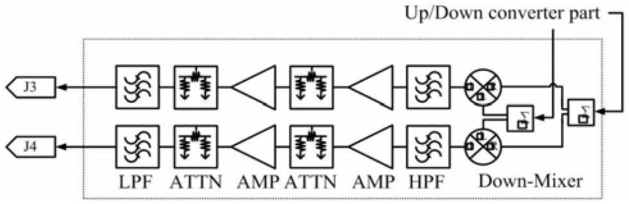


Fig. 6. Block diagram of the baseband block.

difference that leads to an ambiguous measurement for distance and relative speed. The synthesizer signal is conveyed for transmission through the amplifier, a band pass filter (BPF), and an up-mixer. The LO signal is applied where the 3 GHz frequency band can generate a 70 GHz signal through the 4 GHz and 6 GHz frequency bands. The RF signal that is sent through the up-mixer is elevated to 76.5 GHz using a drive amplifier (DRA). The transmitter outputs this signal through the antenna. The received signal is amplified by the LNA and converted to an intermediate frequency (IF) signal though the down-mixer. This signal is dropped to a baseband signal through the I/Q mixer. To split the generated signal and make the beat frequency, which represents the phase difference between the transmitted and received signals, the mixer employs a hybrid coupler. This module uses a mixer for the high-frequency E-band. In this system, the LO is used to generate a signal to convert the signal of interest to a different frequency. The receiver converts the received signal frequency to the IF block through the mixer.

Fig. 6 shows the implemented block of the baseband block. As shown in this figure, the baseband block down-converts the high-frequency signal to the baseband frequency for accurate signal processing. It needs an automatic gain control (AGC) block because of the level difference between the received signals. It can be substituted for an op-amp, which can regulate the signal output level by controlling the gain slope of a high pass filter (HPF). By doing this, it can reduce the level dynamic range of the received signal according to the target distance. This module uses an op-amp that was used to implement the filter and an AGC function to reduce the output change in accordance with the power of the received signal and generate a constant output level. The module uses a band pass filter that consists of an HPF and a low-pass filter (LPF) pair, to reduce the noise from the adjacent frequency band. To maintain constant output power for the signal, this module employs the AGC in the system instead of a general amplifier. If the target is far from the transceiver, there might be low signal power compared to when the target is close to the system. The gain of the processing amplifier can be adjusted by using the AGC elements to maintain a constant signal strength and send the correct information to the DSP though the J3 and J4 ports. If the mixed received signal is digitized and subjected to Fourier transformation within a single period in the DSP, the ambiguities for distance and speed can be resolved by combining the measurement results in accordance with the special equations. The purpose of the radar FEM is to generate an appropriate beat frequency, which will be the key to solving the problem in the DSP.

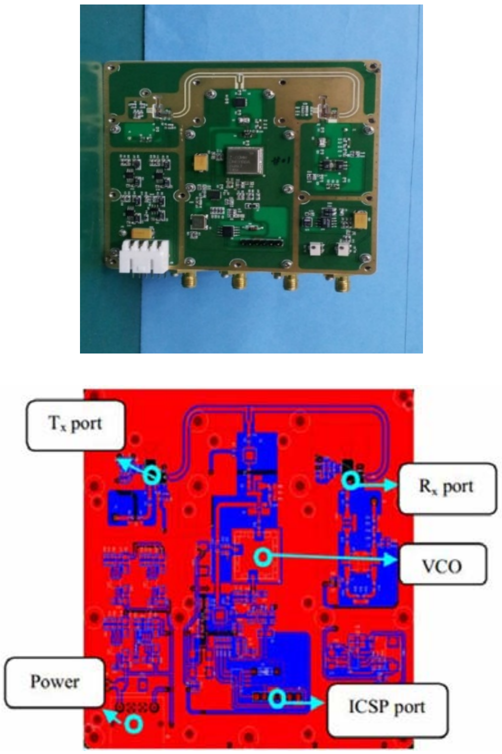


Fig. 7. 77GHz up/down converter & baseband block.

Fig. 7 shows the implemented 77 GHz up/down converter and baseband block.

4. Measurement Results

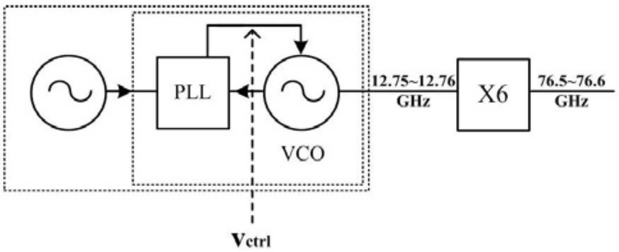
4.1 Block Measurement Result

4.1.1 Synthesizer Test

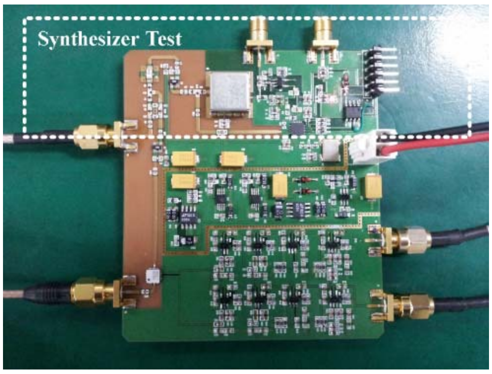
The most important part in this LFM-FSK radar module implementation is the synthesizer. As shown in Fig. 8, the synthesizer was measured by using this PCB. Before frequency multiplication, the test frequency was 3 GHz in the synthesizer. In the synthesizer test, the V_{ctrl} signal waveform controlled the VCO. The LFM-FSK waveform was generated correctly, which shows the output signal of the synthesizer. Fig. 9 represents a transmitted signal's frequency range of 76.45 to 76.55 GHz. According to Fig. 10 by conducting the spectrum analyzer, the bandwidth of the transmitter is 100 MHz. Finally, according to Fig. 11, the chirp time was around 6 ms, which means the measurement resolution time of this block is fast enough.

4.1.2 Loop Back Test

Fig. 12 shows the conducted loop back test for simulation. The beat frequency is the difference between the transmitted and reflected echo signals. The cable used in the transmission line represented a time delay in the actual driving environment. By changing the cable length, the reflected signal was measured with a variety of time delays. Each cable length represented a different driving



(a) Test block diagram



(b) Synthesizer test

Fig. 8. Synthesizer test.

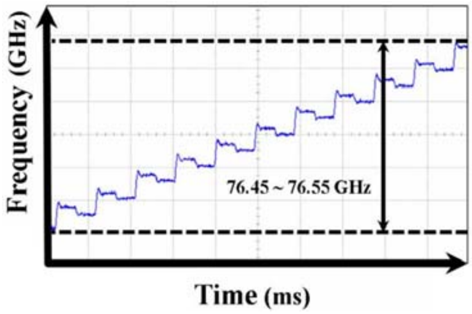


Fig. 9. V_{ctrl} signal waveform of the synthesizer.

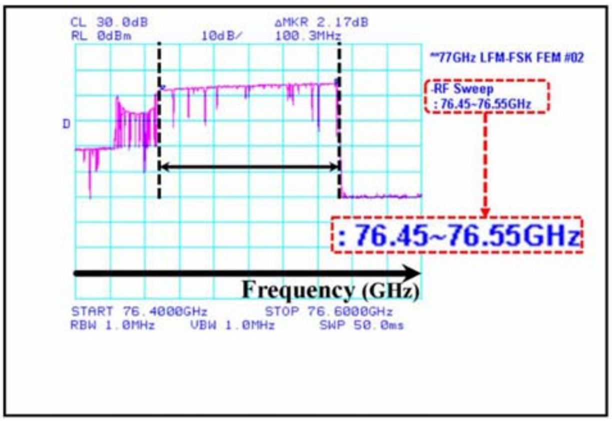


Fig. 10. RF sweep of the synthesizer.

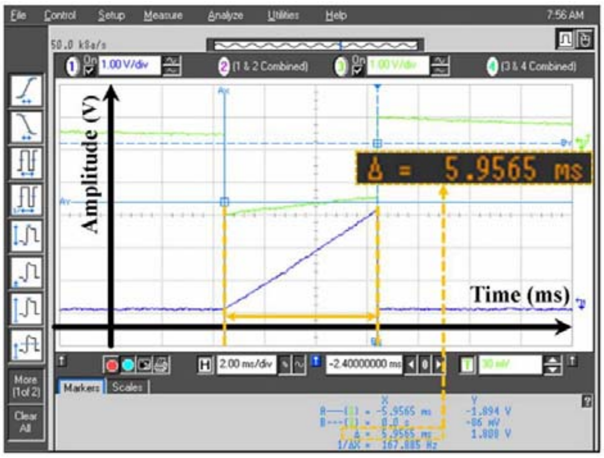


Fig. 11. Chirp time of the synthesizer.

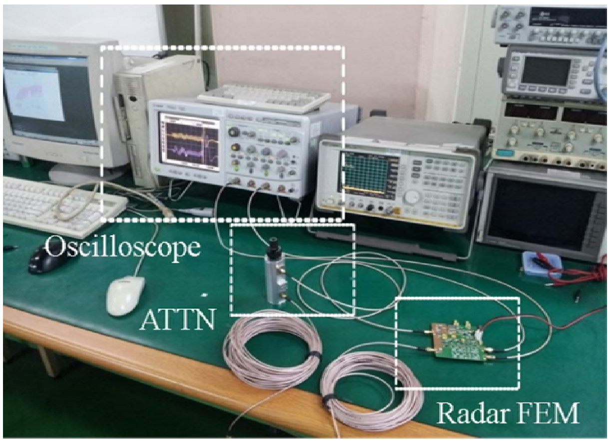
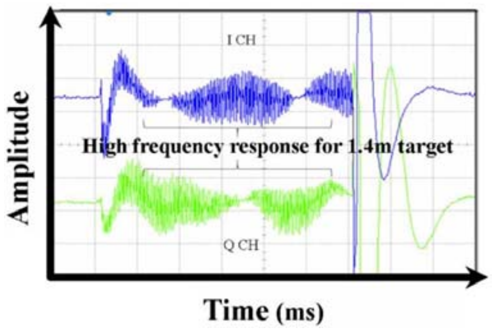


Fig. 12. 77 GHz LFM-FSK radar module.

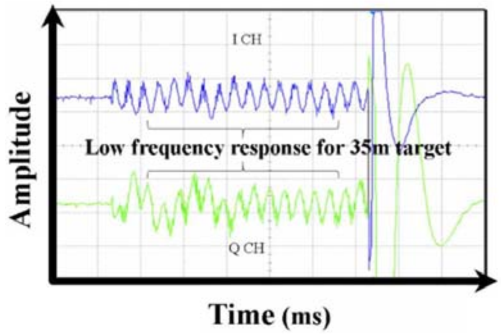
situation; a cable length of 35 m represented a target that was far away from the observer, compared to the 1.4 m length. The loop back test created an artificial delay to check the beat frequency using cable length variation. An attenuator (ATTN) was employed to reduce the tested output power to create conditions similar to actual situations. Fig. 13(a), shows the results of the loop back test when using a 1.4 m cable length. Unlike this result, which assumes that the distance between the target and observer is small, Fig. 13(b) shows that the beat frequency was lower with a longer cable length. This is an important finding: the shorter the distance between the target and the observer, the more likely it is that the module will hand over the beat frequency. Based on this simulation, we can conclude that the implemented radar FEM can operate well with the correct signal information, even in a real traffic environment. A long-length cable represented a target that was far away from the transceiver module, and a short length cable represented the opposite situation.

4.2 System Measurement Result

This paper mainly focuses on the most challenging tasks: generating and conveying the correct transmission waveform in the 77 GHz frequency band to the DSP. The 77 GHz radar FEM was designed using the LFM-FSK method, unlike the conventional FMCW radar. This implementation emphasizes generating the appropriate waveform at a high frequency. The synthesizer test of the



(a) Close situation: 1.4 m cable



(b) Far away situation : 35 m cable

Fig. 13. Loop back test result.

Table 1. Performance of the LFM-FSK radar transceiver.

Module	Parameter	Value
Transmitter	Tx (RF)	76.5 ± 0.05 GHz
	Tx (IF)	2.97 ± 0.05 GHz
	Bandwidth	100 MHz
	Output	+10 dBm
	LO	73.53 GHz
Receiver	Dynamic range	-23 to -112 dBm
	Conversion gain	88 dB
	Rx input P1dB	-22 dBm
	Noise figure	10 dB

developed module confirmed that the LFM-FSK signal generator could produce an adequate signal to transmit. Additionally, the loop back test confirmed that the output frequency of this module works well. Using these methods, the performance of the radar module could be verified in a simulation. The measurement results for the LFM-FSK radar transceiver are summarized in Table 1.

5. Conclusion

This paper presented the first 77 GHz transceiver that applies an LFM-FSK FEM with a frequency synthesizer block, an up/down converter block and a baseband block. The performance of the implemented module was experimentally evaluated twice using a synthesizer and a loop back test. The results of the experiment demonstrated the advantages of the proposed system. Using this implementation for an automotive radar module will promote its commercialization for multi-target detection.

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HyunGi Yoo received his B.S degree in electronic Engineering from Korea Polytechnic University, Korea, in 2010. From 2013, he joined in M.S degree at Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea. His research interests are electronics for electric vehicles, control system for crack detection and analog/RF IC design for automotive radar technology.

MyoungYeol Park received the B.S. degree and the M.S. degree from University of Ulsan, Korea, in 1998. Since 1999, he works for Comotech Corp, as a chief researcher. Comotech Corp. is a leading company developing the world best point-to-point ultra broad-bandwidth wireless link up to 1.25Gbps data rate by using millimeter-wave such as 60 GHz or 70/80 GHz frequency band. Also the company produces high performance components above 18 GHz K-band to 110GHz W-band including 77 GHz automotive radar front-end modules.

YoungSu Kim received the Ph.D. degree in the School of Electrical and Computer Engineering at Ulsan National Institute of Science and Technology (UNIST) in 2014. He now works with Comotech Corp. as a Senior Field Application Manager working on E-band radiolinks and mmW transceiver. Back in 2004, he was with LG-Innotek as a Junior Research Engineer working on 77 GHz radar system and 10 GHz X-band military radars. His research interests include E-band radiolink, RF front-end module & devices in microwave and millimeter-wave frequency ranges for wireless communication systems.

SangChul Ahn received the M.S. degree from University of Ulsan, Korea, in 2004. Since 2009, he works for Comotech Corp, as a Manager in Development Team. His research interests include millimeter-wave radio, radar systems and antenna design.

Franklin Bien is currently an Associate professor in the School of Electrical and Computer Engineering at Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea, since March, 2009. Prior to joining UNIST, Dr. Bien was with Staccato Communications, San Diego, CA as a Senior IC Design Engineer working on analog/mixed-signal IC and RF front-end blocks for Ultra-Wideband (UWB) products such as Wireless-USB in 65nm CMOS technologies. Prior to working at Staccato, he was with Agilent Technologies and Quellan Inc., developing transceiver ICs for enterprise segments that improve the speed and reach of communications channels in consumer, broadcast, enterprise and computing markets. His research interests include analog/RF IC design for wireless communications, signal integrity improvement for 10+Gb/sec broadband communication applications, circuits for wireless power transfer technologies, and electronics for electric vehicles.