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Research Article

High-Accuracy AM-FM Radar with an Active Reflector

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An amplitude-modulated and frequency-modulated (AM-FM) radar with an active reflector to produce high-accuracy distance measurements is proposed and demonstrated in this paper. The proposed radar consists of an AM-FM base module and an active reflector. The combination of AM and FM modulations resolves ambiguity of the absolute distance in typical AM radars, while improving range accuracy in typical FM radars with narrow bandwidth. Also, the active reflector, which translates the frequency of the received signal, resolves the problem of phase detection interference due to the direct Tx-to-Rx leakage in AM radars. In this paper, the operating principle, experimental tests, and analysis are presented. The implemented AM-FM radar operates in X-band (Tx: 10.5 GHz, Rx: 8.5 GHz) with the 620 MHz bandwidth. The measured range accuracy of less than ±10 mm at a distance of 70 m is obtained.

1. Introduction

Accurate noncontact distance measurement systems are widely used in various applications. Position measurement methods can be divided into different categories depending on the utilized technologies such as ultrasound, GPS, laser, and RF/microwave waves [1]. Attempts to use optical fibers for the detection of cracks and vibrations in bridges or tunnels have also been reported [2].

These distance measurement technologies have their own advantages and disadvantages. An ultrasonic system is limited to short-range distances in a small area because of its low precisions; it is widely employed in rear bumper proximity sensors of commercial vehicles. The accuracy of typical GPS-based distance measuring systems is approximately 10 m, and, therefore, it is not suitable for the detection of structural faults. Laser sensors have a range of up to several hundred meters and mm-level accuracy. However, their performance degrades rapidly under the influence of heavy raining or foggy weather and with lens or reflector contamination. An alignment of the laser beam is also required for accurate measurements. On the other hand, a radar-based sensor, using electromagnetic radiation, can operate reliably under harsh weather conditions. Therefore, the radar technology is widely used not only in military systems but also in a number of industrial applications such as automotive radars, blind spot monitoring, and level gauges. Active researches have been performed for the high-resolution radar technology with the mm-level accuracy [3–9]. Both ultrawideband (UWB) [3–7] and wideband frequency-modulated continuous-wave (FMCW) [8, 9] techniques were used to achieve this level of precision.

In this paper, we propose a practical ranging system with mm-accuracy using AM-FM radar combined with the active reflectors. The frequency translating active reflector is utilized in order to significantly reduce the phase detection ambiguity in AM radars related to interference or multipath signal reception. The proposed AM-FM radar uses narrower bandwidth as compared with other methods.

2. AM-FM Radar and the Active Reflector

2.1. Overview of the Proposed AM-FM Radar. The proposed AM-FM radar module combines amplitude modulation (AM) and frequency modulation (FM) based radars with an active reflector. A simplified block diagram of the proposed system is shown in Figure 1. The proposed system consists

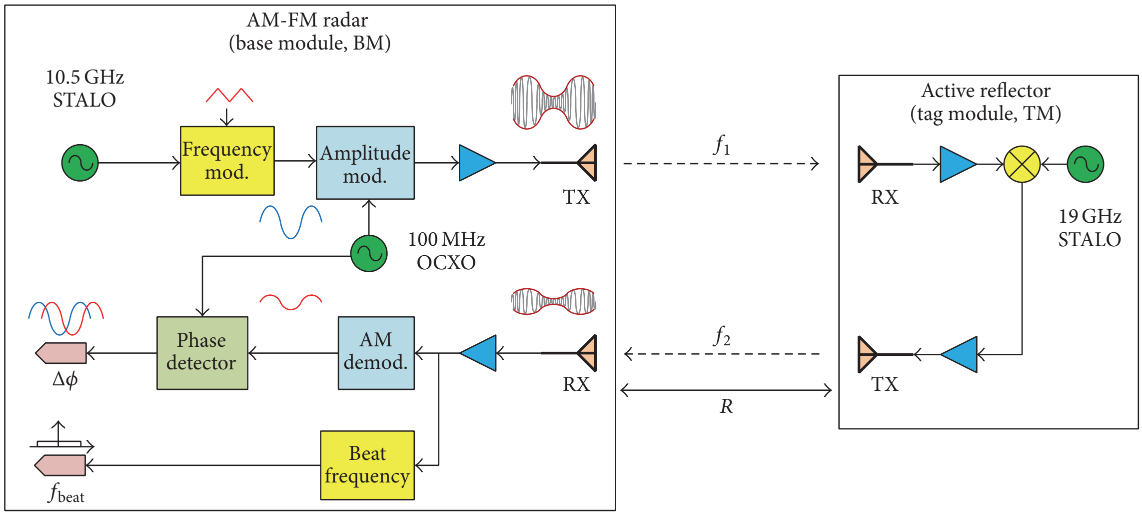


Figure 1: Simplified block diagram of the proposed AM-FM radar.

of two parts: an AM-FM radar module (base module, BM) and an active reflector module (tag module, TM). In the AM-FM radar base module, a CW microwave signal is first frequency-modulated and then amplitude-modulated. The AM-FM signal is transmitted toward the active reflector. The active reflector at the target location receives the AM-FM signal, translates the center frequency of the signal, and retransmits the signal with amplification. Then, the base radar module receives the retransmitted signal from TM and determines the absolute distance with combination of the beat frequency due to FM modulation and phase delay due to AM modulation. The beat signal due to FM modulation helps to obtain the rough absolute distance on the order of 1 m. The phase delay due to AM modulation helps to resolve the distance with mm-accuracy. The ambiguity of absolute distance in AM radars is overcome with the combination of the FM modulation. Also, with an active reflector, which translates frequency of the received signal and retransmits it toward the base system, the phase detection interference problem in typical AM radars can be resolved.

In the next paragraphs, FMCW and amplitude-modulated continuous-wave (AMCW) radar principles are briefly summarized, and the benefits of adapting active reflectors are described.

2.2. FMCW Radar. A typical bistatic and homodyne FMCW radar configuration [10, 11] is adapted for the proposed AM-FM radar system. In general radar system, range accuracy is a concept that should be distinguished from range resolution but is related to it. The range resolution (δR) and bandwidth (B) relation is

$$\delta R = \frac{c}{2B}, \tag{1}$$

where c is speed of light. High range resolution increases range accuracy [12]. Therefore, to achieve high accuracy in radar system, wide bandwidth is essentially needed.

On the other hand, another limitation is present due to the signal processing. Typically, in order to acquire the beat frequency of the received signal, an analog beat signal is first sampled using an analog-to-digital converter, and then the fast Fourier transform (FFT) algorithm is utilized. As the result of FFT, the beat frequency is discretely distributed. The maximum beat frequency error equals the FFT step size, and the differences exist between the real beat frequency and the discrete beat frequency by FFT [13]. The FFT step size (Δf) can be calculated as follows:

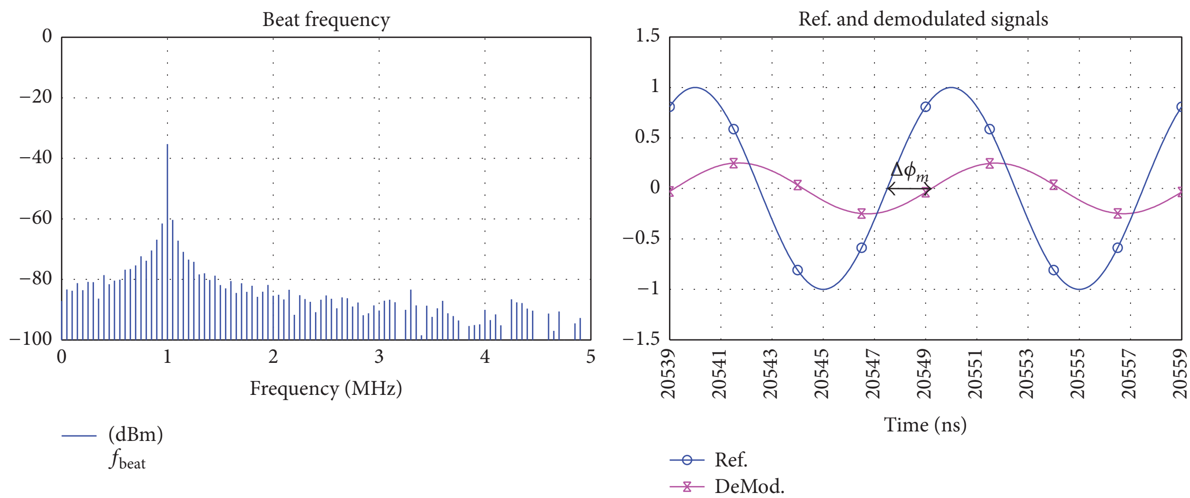
$$\Delta f = \frac{f_s}{N_s}, \tag{2}$$

where f_s is the sampling frequency and N_s is the total number of data samples during the sampling period. Thus, the range step size ($\Delta R_{\max}^{\mathrm{FFT}}$) according to the FFT step size is as follows:

$$\Delta R_{\max}^{\mathrm{FFT}} = \frac{cT\Delta f}{2B} = \frac{cT}{2B} \cdot \frac{f_s}{N_s}, \tag{3}$$

where T is chirp period. As shown in (1) and (3), high range accuracy requires both wide frequency bandwidth and high-performance hardware.

2.3. AMCW Radar. The AMCW radar system was reported in [14], and certain drawbacks of the AMCW radar were pointed out. First, the maximum measurable distance, without ambiguity, is limited to the wavelength of the modulation frequency. Second, the leakage power between transmitter (Tx) and receiver (Rx) antennas induces the phase detection error. In spite of these problems, the AMCW radar has several advantages: (1) a very simple structure and (2) high range accuracy achievable by an increase in the modulation frequency. Consequently, the AMCW method was used in some special applications such as a short-range radar and plasma diagnostics [15].



(a) FFT result of the beat signal

(b) Phase difference

FIGURE 2: Typical cases of beat frequency and phase difference.

TABLE 1: Range errors in the AMCW radar with no leakages.

Phase detection error	$f_m = 10$ MHz	$f_m = 50$ MHz	$f_m = 100$ MHz
1°	41.67 mm	8.33 mm	4.17 mm
5°	208.33 mm	41.67 mm	20.83 mm
10°	416.67 mm	83.33 mm	41.67 mm

The transmitted signal of the AMCW radar is amplitude-modulated, consisting of the carrier (f_c) and double side-bands ($f_c \pm f_m$) in the frequency domain. The distance R_{AM} between the radar and the target is

$$R_{AM} = \frac{c \cdot \Delta\phi_m}{4\pi f_m}, \quad (4)$$

where $\Delta\phi_m$ is the phase difference between the reference and the received signals and f_m is the modulation frequency. Table 1 summarizes the range errors corresponding to the different phase detection errors and f_m. Here, the ambiguity of absolute distance exists depending on the modulation frequency. Distance ambiguity of AM radar with 100 MHz modulation frequency is 1.5 m.

In a typical AMCW radar, a portion of the transmitted signal is routed to the received signal path through Tx/Rx antennas or isolators. The major factor causing an error in the AMCW radar is the ratio of the main echo signal and the direct Tx-to-Rx leakage signal. For ±1° phase accuracy, the echo signal should be at least 12 dB stronger than the direct leakage signal. However, the direct leakage power is kept constant, while the echo signal decreases as the distance R increases. In the proposed AM-RM radar, a frequency-shifting active reflector removes the problem of the direct Tx-to-Rx signal leakage.

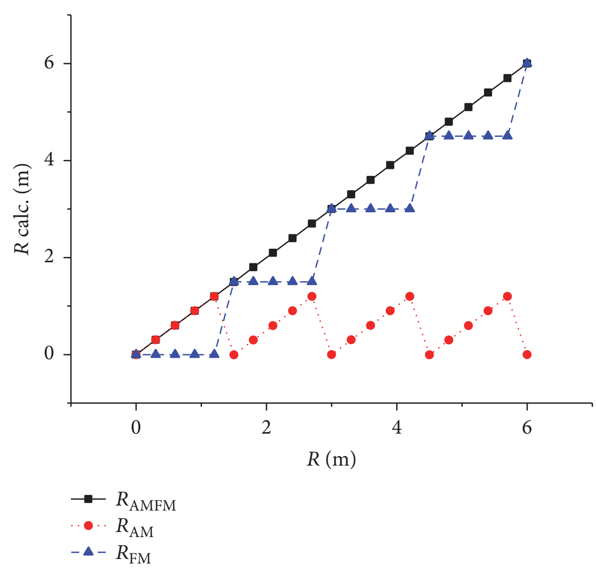


FIGURE 3: Distance estimation of AMCW (red), FMCW (blue), and combination of AM-FM (black) radar.

2.4. Combined AM-FM Radar. The absolute distance between the AM-FM radar base module and the active reflector (R_{AMFM}) can be calculated as follows:

$$R_{AMFM} = R_{AM} + R_{FM} = \frac{c \cdot \Delta\phi_m}{4\pi f_m} + \frac{cTf_{beat\_FFT}}{2B}, \quad (5)$$

where R_{AM} is the range due to $\Delta\phi_m$ of the AMCW radar and R_{FM} is the range due to the FFT result of beat frequency (f_{beat_FFT}) of the FMCW radar. R_{FM} is discrete due to the FFT step size, but R_{AM} varies continuously within unambiguous region. Figure 2 presents typical cases of f_{beat_FFT} and $\Delta\phi_m$. The absolute distance estimation by combining the FM and AM distance measurements using (5) is shown graphically in Figure 3. As a result, high-accuracy distance measurement can be achieved.

2.5. Active Reflector. An active reflector is typically used in the radar system for calibration. The active radar calibrator (ARC) is composed of two antennas (sending and receiving) and an RF amplifier. Despite its small size, it is possible to obtain a high standard radar cross section (RCS) value in the radar system [16]. In the proposed AM-FM radar system, the active reflector translates the frequency of the incoming signal and retransmits it toward the radar base module. Adopting the active reflector has two advantages. First, the problem of the direct Tx-to-Rx leakage through antennas or isolators can be solved due to frequency translation, removing the serious drawback of the AMCW radar system. Second, a high conversion gain can be achieved by splitting the gain between the base module and the active reflector module.

3. Implementation and Measurement Results

3.1. Design and Implementation. The proposed AM-FM radar consists of two parts as presented in Figure 1. One is the base module (BM, AM-FM radar) and the other is the tag module (TM, active reflector). In the BM, a 100 MHz OCXO provides the reference signal for the phase detector, as well as the baseband signal of the amplitude modulation. The OCXO is also used as a reference of the PLL in the 10.5 GHz stable local oscillator (STALO) and as a system clock for the direct digital synthesizer (DDS), providing the linear frequency modulation. An amplitude-modulated and frequency-modulated 10.5 GHz signal is transmitted through the Tx antenna of the BM and is received by the Rx antenna of the TM at the target location. The TM converts the center frequency of the received signal from 10.5 GHz to 8.5 GHz with the help of 19 GHz STALO and retransmits the filtered and amplified signal using the Tx of the TM. Then, the BM receives the 8.5 GHz AM-FM signal and demodulates it into the phase delayed signal which is produced by the envelope detector and also into the beat signal with the help of the frequency mixer. The combination of the phase difference and the beat frequency enables calculating the absolute distance of the target with high accuracy. The overall gain budget is calculated using a spreadsheet and verified with the system simulator, NI AWR Microwave Office (MWO).

Figure 4 shows the fabricated RF front-end modules of the AM-FM radar. For the RF circuit, 20 mil thick RO4003 ($\varepsilon_r = 3.38$; $\tan\delta = 0.0027$) substrate is used. Passive components such as the filter, power divider, and power detector were simulated using the 2.5 D EM simulator of the NI AWR MWO. RF PCBs are mounted in a metal housing in separate channels. Regulators for the bias and other circuits are mounted on the bottom side of the housing.

The transmit power of the BM is +17.6 dBm. The FM chirp signal is generated using the DDS. With the FM bandwidth of 420 MHz, the chirp period of 200 μs is achieved for both rising and falling. The AM signal is generated using the RF mixer and the combiner. The modulation index is 20%. Total RF bandwidth results in 620 MHz. The Tx spectrum of the BM is shown in Figure 5(a), and the down-converted spectrum of the TM is shown in Figure 5(b). The IQ-mixer and NI DAQ are used for the phase calculation, while the beat frequency is measured with the aid of the NI-SCOPE. Detailed system specifications are summarized in Table 2.

Table 2: Proposed AM-FM radar specifications.

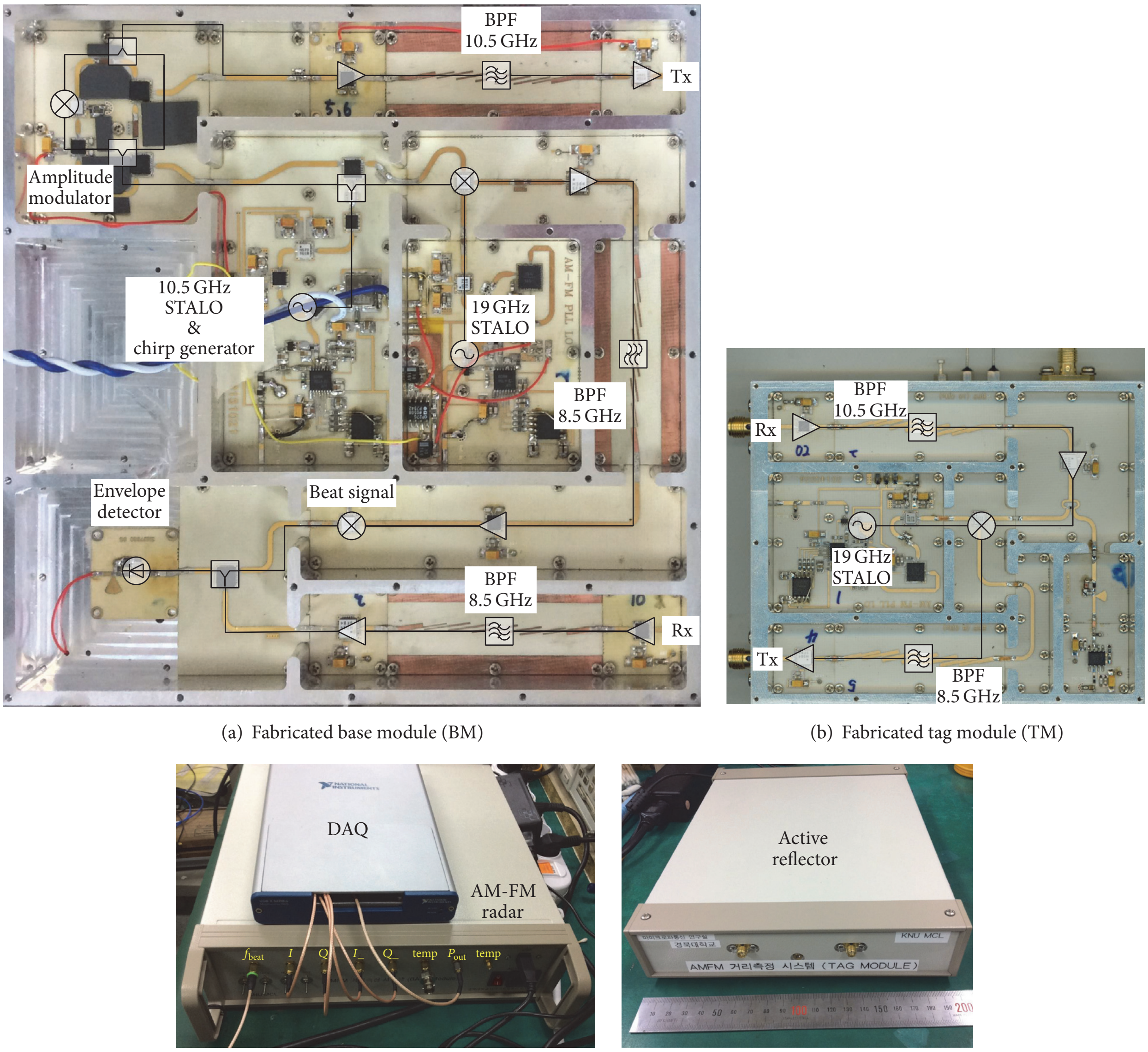
Parameters	Unit	Value
Base module		
Tx power	dBm	17.6
Tx frequency	GHz	10.5
Rx frequency	GHz	8.5
AM modulation index	%	20
AM conversion gain	dB	3.5
FM bandwidth	MHz	420
FM sweep frequency	kHz	2.5
FM conversion gain	dB	61.5
Tag module		
Rx frequency	GHz	8.5
Tx frequency	GHz	10.5
Conversion gain	dB	32
Antenna (horn)		
Gain	dBi	24
Beam width	°	20

3.2. Measurements. To verify performance of the proposed system, outdoor experiments were carried out at a University parking lot. The measurement setup is presented in Figure 6. The distance between the BM and the TM was varied from 71 m to 73 m. The phase difference and the beat frequency were measured at 10 cm intervals. For fine measurements, distance intervals of 5 cm and 1 cm were used.

The measured phase difference and beat frequency are plotted in Figure 7(a). A commercial data acquisition module (NI USB-5133) and its FFT function software were used to analyze the FM data. With 10 MHz of f_s and number of samples of 1024, the FFT step size was 9.766 kHz. In the proposed system, the FM bandwidth is 420 MHz, and the sweep frequency is 2.5 kHz. The distance of phase ambiguity in the AM radar (100 MHz) is 1.5 m, and the corresponding FFT step for 1.5 m distance is 21 kHz. Therefore, there are ~2 beat frequency hops within a phase change of 2π in the AM measurement. The measured beat frequency of the FM signal is divided by 21 kHz and a truncated integer bin number is obtained to calculate the base distance estimated by the FM measurement (i.e., (bin number) × 1.5 m). Then, the distance calculated from the phase delay of the AM modulation signal is added to obtain the absolute distance using (5) as shown in Figure 7(b).

A zoomed portion of the fine-measured data in Figure 7(b) is plotted in Figure 7(c) with the calculated error. From the figure, the precision of the tested system is estimated as ±10 mm.

3.3. Discussion. Competing technologies for the high-accuracy distance measurements include FMCW and UWB.



(a) Fabricated base module (BM)

(b) Fabricated tag module (TM)

(c) AM-FM radar module (BM)

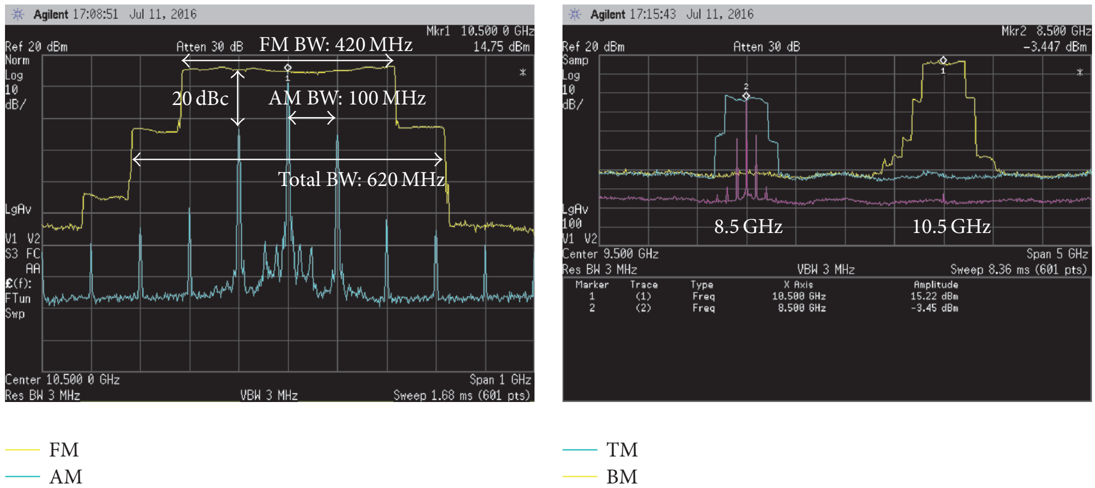
(d) Active reflector module (TM)

Figure 4: Fabricated RF front-end modules (a, b) and the implemented AM-FM radar (c, d).

These methods use wide frequency bandwidth from 1000 to 5000 MHz with the error level from 5 mm to 20 cm. Table 3 presents a summary of various distance measurement systems, associated bandwidth, and errors. As can be seen, the proposed system has been demonstrated to achieve high accuracy, in spite of using narrower bandwidth as compared with other systems.

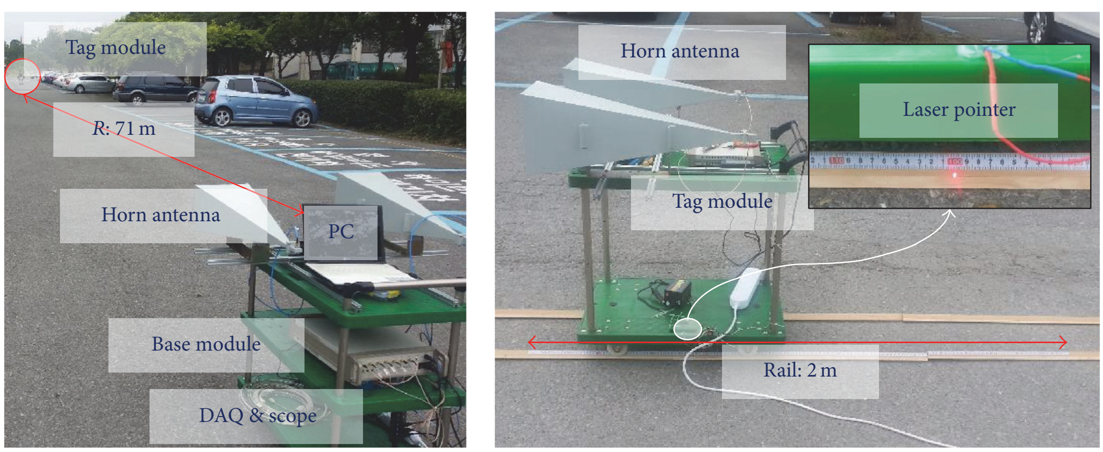
4. Conclusion

A high-accuracy distance measuring system combining the AM and FM radars and the active reflector is proposed. Its operating principle, experimental tests, and analysis are presented. The proposed system operates at center frequencies of 10.5 GHz (Tx) and 8.5 GHz (Rx) and occupies 620 MHz bandwidth around each of the center frequencies. The transmit power was +17 dBm, and standard horn antennas with a gain of 24 dBi were used. Compared with other methods, the proposed system used narrower frequency bandwidth but achieved high range accuracy. The measured distance error with respect to the absolute distance was below ±10 mm. From these results, the proposed AM-FM radar is expected to be applied to various fields that need high-accuracy distance measurements including detection of the vibration or cracks in concrete structures or bridges. Also, accurate distance monitoring for multiple target locations is possible with multiple active reflectors with their corresponding IDs.

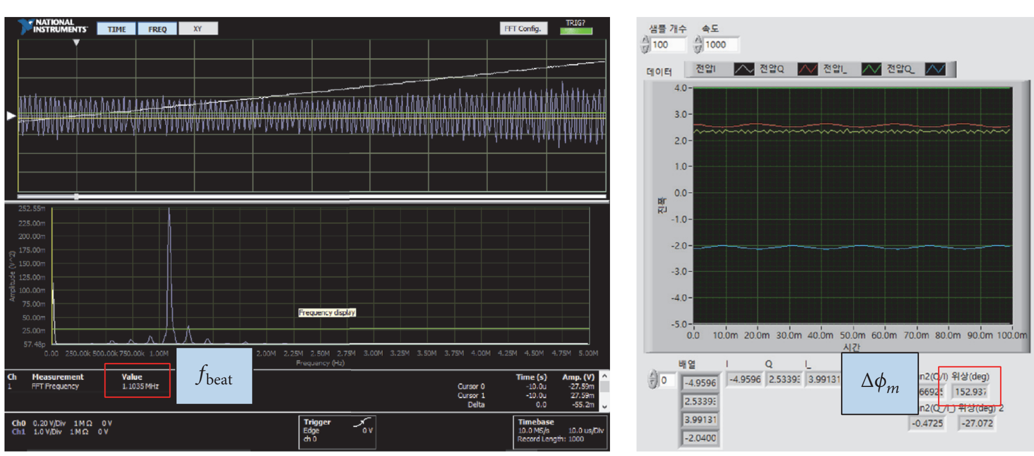


(a) Tx spectrum of the base module (BM)   (b) Frequency converted spectrum of the tag module (TM)

FIGURE 5: Frequency spectra of the fabricated system.

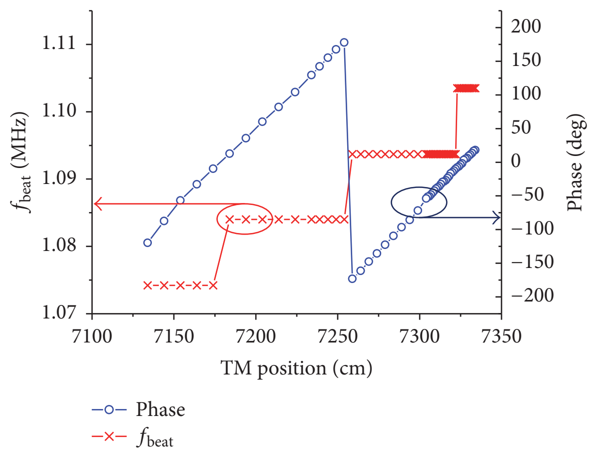


(a) Base module   (b) Tag module

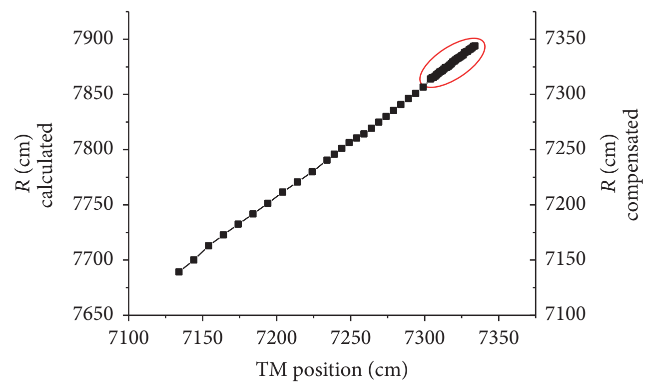


(c) NI-SCOPE GUI for f_{beat} (d) LabVIEW program for $\Delta\phi_m$

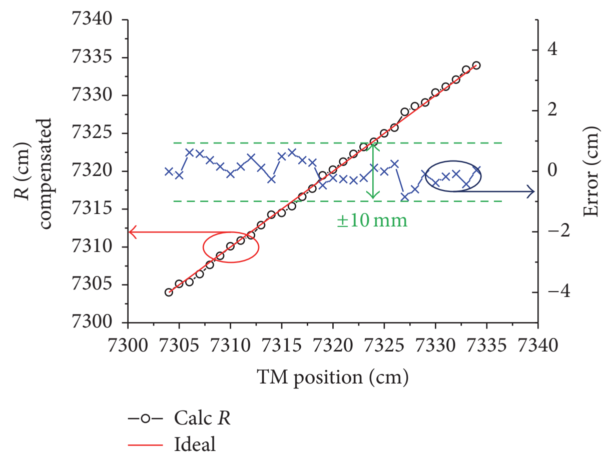
FIGURE 6: Outdoor measurement setup.



(a) Measured beat frequency (f_b) and phase delay ($\Delta\phi$)



(b) Calculated distance (R) using f_b and $\Delta\phi$



(c) Zoomed up portion of Figure 7(b) and the distance error

FIGURE 7: Measurement results of proposed system in outdoor fields.

TABLE 3: Comparison of high-accuracy radar systems.

	System architecture	Center frequency	Bandwidth	Error	Operating range
This work	*AM-FM*	*10.5/8.5 GHz*	*620 MHz*	*10 mm*	*70 m*
[3]	UWB	5.4~10.6 GHz	5200 MHz	5 mm	5 m
[4]	UWB	7~8 GHz	1000 MHz	1.7 cm	10 m
[5]	UWB	3.7~5 GHz	1300 MHz	20 cm	8 m
[6]	UWB	3.2~5.2 GHz	2000 MHz	1 cm	8 m
[7]	UWB	0.01~5 GHz	4990 MHz	1.5 cm	2 m
[8]	FMCW	5.8 GHz	—	10 cm	40 m
[9]	FMCW	5.8 GHz	150 MHz	18 cm	40 m

Competing Interests

The authors declare that they have no competing interests.

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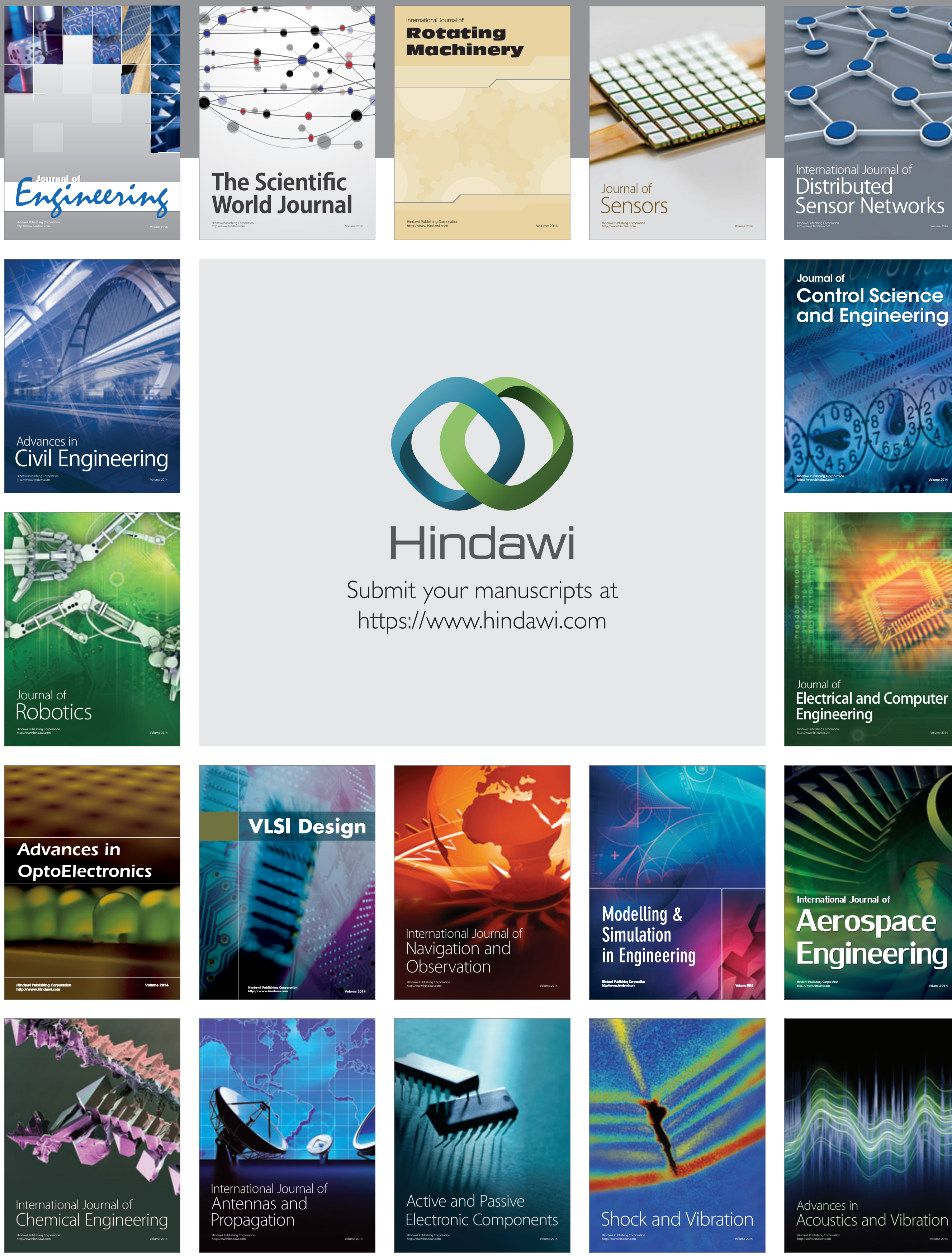
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