A Dual PLL FMCW Radar with a Digital Time Control Technique for High-Resolution Wall-Penetration Applications

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***Abstract*—In wall-penetrating radar applications, large wall-reflections could cause several problems. A range-gate filter is used to eliminate the wall-clutter in conventional frequency-modulated continuous-wave (FMCW) radars. However, a very high-order high-pass filter (HPF) is required to fully reject the wall-clutter. Moreover, a reconfigurable HPF or several HPFs are needed to adaptively operate when the radar-to-wall distance is changed. To overcome these problems, we use the characteristics FMCW radar and phase-locked loop: (1) The FMCW radar generates beat-frequencies depending on the time difference between the chirp signals of the mixer's local oscillator (LO) port and radio frequency (RF) port. Therefore, the beat-frequencies are adjusted by controlling the time-difference; (2) The PLL tracks and locks onto the reference clock, and it uses only the phase information of the reference clock. An advanced digital control technique allows the half-period shifting of the reference clock. When the reference clock is half-period shifted, the PLL locks onto the shifted phase, and its output signal (chirp signal) has a corresponding delay. The proposed FMCW radar uses two-PLLs with a reference distribution network; one PLL generates transmitting chirp signals, and the other generates receiving chirp signals. The reference distributor not only distributes the reference clock to the two PLL's reference paths, but also controls the phase using a digital control technique. By controlling the reference clock phase, the desired time-difference between the chirp signals is achieved. This technique allows a low-order HPF to fully attenuate wall-clutter and decouple the relationship between the radar-to-wall distance and the HPF's order and the relationship between the radar-to-target distance and the HPF's cut-off frequency. The measured results show that a second-order HPF with a 220 kHz cut-off frequency attenuates more than 30 dB when the radar-to-wall distance is 4.276 m and the radar-to-target distance is 5.724 m. The emulation results are well agreements with the theory.**

Keywords*—*digital time-control; frequency-modulated continuous-wave (FMCW) radar; high-pass filter (HPF); phased-locked loop (PLL); wall-clutter

I. INTRODUCTION

Recently, high-resolution wall-penetrating radars have been reported [1–4]. In these wall-penetration applications, radars can be suffer from considerable wall reflections [1], [3–4]. The wall-clutter can invoke several problems such as reducing a receiver's dynamic range. Frequency-modulated continuous-wave (FMCW) radars can overcome these problems by using a range-gate filter. The filter fully rejects clutter, including wall-clutter.

However, conventional homodyne FMCW radars require a very high-order high-pass filter (HPF) when the wall-to-target distance is short [4]. Moreover, these radars require either a reconfigurable HPF or several HPFs to adjust the HPF's order and cut-off frequency. For example, to attenuate the wall-clutter by more than 30 dB with a 25,000 GHz/s chirp rate homodyne FMCW radar, a fifth-order HPF with a 500 kHz cut-off frequency is required when the radar-to-wall distance is 1.5 m and the radar-to-target distance is 3 m, and a thirteenth-order HPF with a 1 MHz cut-off frequency is required when the radar-to-wall distance is 4.5 m and the radar-to-target distance is 6 m. Implementation of several very high-order HPFs entails high costs.

A FMCW radar with a delay-line architecture was proposed to moderate the filter specification and lower the filter order [4]. In [4], a delay-line is used in a local-oscillator (LO) path to delay a chirp signal (RX chirp) entering the mixer's LO port. Thus, the time-difference between the mixer's LO port signal (RX chirp) and RF port signals (wall-clutter and target signal) decreases. As a result, the beat-frequencies of the wall and the target decreases, and the ratio of the target beat-frequency to the wall beat-frequency increases. The increase in the ratio means that the filter specification is moderated, and a low-order HPF meets the filter specification [5]. This delay-line FMCW architecture is useful in fixing short-range wall-penetrating radars.

However, the delay-line technique can be applied only to specific wall-penetration applications for several reasons: (1) a variable delay-line or several long delay-lines are needed to achieve the optimum ratio of the target beat-frequency to wall beat-frequency when the radar-to-wall distance is varied; (2) the delay-line introduces high signal loss when the radars uses a high frequency such as an X-band [6]; and (3) side-lobes

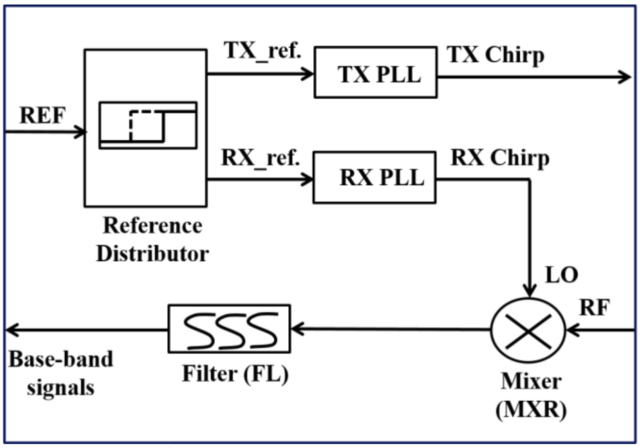

Fig. 1. Core blocks of the proposed radar.

increase because the chirp amplitude is modulated or the chirp frequency-linearity is distorted by the delay-line [7]. In sum, delay-line FMCW radars are not suitable for high-resolution non-fixed wall-penetration applications.

The above problems occur because the desired time-difference is obtained by delaying a high frequency analog domain signal (RF or LO chirp signal). In such a high frequency analog domain, the external circuits make a high loss. Moreover, it is hard to adopt digital techniques to control the time-difference. To avoid these problems, the proposed FMCW radar achieves a controllable time-difference by using a low-frequency digital domain signal.

A phased-locked loop (PLL) is a component that locks onto the phase of the reference clock. When the phase of the reference clock is changed, the PLL tracks and locks onto the changed phase, and then generates a corresponding delay to output signal (chirp signal). Therefore, a desired chirp delay is obtained by repeating the phase-shifting of the reference clock.

This technique has many advantages: (1) A long-delayed chirp signal is available, and even an infinitely delayed chirp signal is theoretically possible; (2) The amplitude loss or modulation of the reference clock is a less important because the PLL only uses a phase information, and the reference clock is a low-frequency signal; (3) This technique does not introduce any amplitude loss or modulation into the chirp signal; (4) Continuous half-period shifting is available. Because a PLL reference clock is a digital-domain signal, digital phase-control techniques can be applied, such as slipping clock or changing the edges of the reference clock. It allows a continuous half-period shifting [8].

Section II provides the measurement results, and Section III presents the conclusions.

II. MEASUREMENT RESULTS

The proposed technique was verified using a radar emulator as shown in Fig. 2. An external signal generator provides a 400 MHz reference clock. The reference clock is split into two-paths by a reference distributor; one is directly sent to the TX PLL reference port and the other to the RX PLL reference port through a phase controller. The phase controller provides the half-period shifting of the reference clock. In the 400 MHz reference clock, the half-period corresponds to 1.25 ns. When the half-period delayed, the RX PLL tracks and locks onto the delayed phase and the output (RX chirp) is delayed by 1.25 ns. Each half-period shift should result in a 31.25 kHz frequency variation in beat-frequencies when the chirp rate is 25,000 GHz/s.

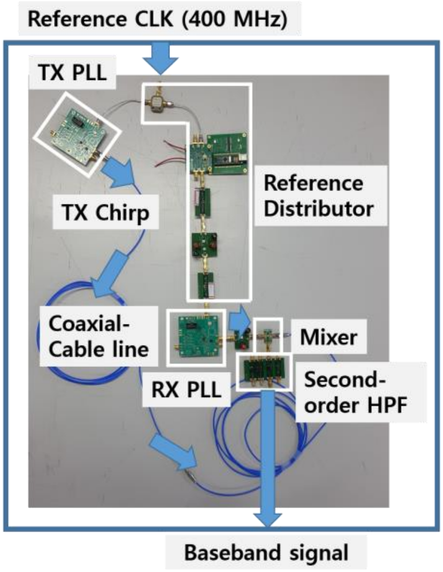

Fig. 2. Radar emulator to verify the proposed technique.

The TX PLL and the RX PLL generate 9.0-10.0 GHz chirp signals during 100 μs (rising time = falling time: 50 μs, the corresponding chirp rate: 25,000 GHz/s). The TX chirp signal passes through coaxial-cable lines. One line has a 28.51 ns delay and the other line has a 38.16 ns delay. The line with a 28.51 ns delay represents a wall located at 4.276 m and the other line with a 38.16 ns delay represents a target located at 5.724 m. The corresponding wall-to-target distance is about 1.45 m. After passing the coaxial-cable line, the TX chirp signal enters the mixer's RF port.

The RX chirp signal is amplified to fully drive the mixer's LO port and enters the mixer's LO port. Then, the mixer generates beat-frequencies corresponding to the time-difference between the mixer's RF port and the mixer's LO port chirp signals. Finally, the generated beat-frequency signals are filtered out by a second-order Butterworth HPF with a 220 kHz cut-off frequency, and measured by the external signal analyzer.

To design the second-order Butterworth HPF with a 220 kHz cut-off frequency, a 28.17 μH shunt inductor and an 11.27 nF series capacitor are needed. In implementation, a 30 μH shunt inductor and a 12 nF series capacitor are used. Note that the cut-off frequency would be a little varied due to several reasons (the finite quality factor of the lumped components, the reactance variation of the lumped components, the zero DC bias of the mixer's IF port by the shunt inductor).

Repeating the phase-shifting a 100 times resulted in a 3.122 MHz frequency variation in beat-frequency. The corresponding average frequency variation was 31.22 kHz. The second-order HPF attenuated by more than 30 dB for a wall located at 4.276 m; it attenuated by 0.1 dB for a target located at 5.724 m. These results tally with the theoretical predictions.

III. CONCLUSION

The proposed FMCW radar successfully eliminates wall-clutter with a low-order HPF by using two PLLs and a digital time-control technique. Due to the PLL using only the phase information of the reference clock, the digital time-control technique does not introduce any amplitude loss or modulation in a chirp signal. Further, the advanced digital control technique allows the continuous half-period shifting; consequently, the time difference between the RX and TX chirp signals is controlled. As a result, the relationship between the radar-to-wall distance and the HPF's order and the relationship between the radar-to-target distance and the HPF's cut-off frequency are decoupled. The measurement results show that a second-order HPF attenuates by more than 30 dB for a wall located at 4.276 m and attenuates by 0.1 dB for a target located at 5.724 m. The measured results correspond well with the theoretical predictions. Due to the abovementioned characteristics, the proposed radar is highly appropriate for non-fixed high-resolution wall-penetration applications.

Acknowledgment

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References

[1] G. L. Carvat, L. C. Kempel, E. J. Rothwell, C. M. Coleman, and E. L. Mokole, "A through-dielectric radar imaging system," IEEE Trans. Antennas Propag., vol. 58, no. 8, pp. 2594–2603, Aug. 2010.

[2] Y. Yang and A. E. Fathy, "See-through-wall imaging using ultra wideband short-pulse radar system," in Proc. IEEE Antennas Propag. Soc. Int. Symp., pp. 334–337, 2005.

[3] N. Maaref, P. Millot, C. Pichot, and O. Picon, "FMCW ultra-wideband radar for through-the-wall detection of human beings," in Proc. Int. Radar Conference – Surveillance for a Safer World, pp. 1-5, Oct. 2009.

[4] B. Kim et al., "A Clutter Rejection Technique Using a Delay-line for Wall-penetrating FMCW Radar," IEICE Trans. Electron, vol. E99–C, no. 5, pp. -, 2016. (In process of publication)

[5] J. S. Hong and M. J. Lancaster, Microstrip Filters for RF/Microwave Applications, 2001 :Wiley

[6] D. M. Pozar, Microwave Engineering 3rd ed., 2005: Wiely

[7] H.D. Griffiths, "The effect of phase and amplitude errors in FM radar," in IEE High Time-Bandwidth Product Waveforms in Radar Sonar Colloq., London, U.K., 1991, pp. 9/1-9/5.

[8] Analog Device [Online]. Available: http://www.analog.com/en/index.html