Fast chirp FMCW Radar in automotive applications

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Keywords: FMCW Radar, fast chirp modulation, open loop modulation, automotive radar, range resolution

Abstract

FMCW (frequency-modulated continuous wave radar) modulations have been popularly implemented in the automotive radar applications. This document demonstrates system requirement for a new FMCW modulation - fast chirp modulation. It largely improves the range resolution compare to general automotive FMCW Radar system. A practical RF-front end system is also presented at the end of the paper.

1 Introduction

Automotive industry shows great interest in autonomous driving systems. It may decrease the fatalities rate to zero. A complete sensors system is the key for the autonomous driving systems. Compare to other automotive sensors, such as camera, laser etc., radar plays an important role due to its inherent advantages [1]. First of all, radar provides stable performance for night and raining environment. Furthermore, radar can easily detect the mobility of the object. In addition, with emerging technology of silicon germanium (SiGe) technology [2-3], 77GHz automotive Radar may be supported with affordable price. Therefore, there is a strong increasing demand on millimetre wave (mmW) Radar in automotive application.
Fig. 1 shows some typical applications, e.g. adaptive cruise control (ACC), blind-sport detection (BSD), line change assistant, etc. Table I depicts performance requirement of those automotive Radars [4].

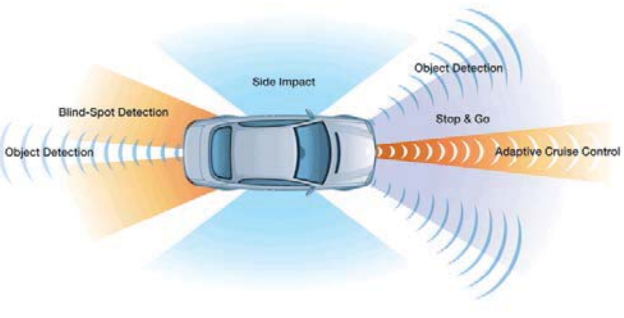

Fig. 1. Automotive radar applications.

FMCW (frequency modulated continues wave) radar has been popularly used in automotive radar nowadays. It may detect both range and speed of the object simultaneously. From the next section, this document first reviews the basic concept of the FMCW modulation. The limitation of the classic FMCW in automotive application is also discussed. Then, we present the concept of the fast chirp modulation and its application with open loop concept in automotive radar system. After that, a practical system is presented as an example in section 4. At last, conclusion and further discussion are shown.

Table I. Typical performance of automotive radars

Type	Detection range	Angle
long range	200m	18°
middle range	60m	60°
short range	0.2-30m	80°

2 FMCW modulation

FMCW Radar standards for frequency-modulated continuous wave radar. It is a radar transmitting a continuous carrier modulated by a periodic function such as a sinusoid or sawtooth wave to provide range data [5].
Fig. 2 shows the principle of the FMCW [6]. Linear frequency modulated signals are sent by transmitter. The signals will be reflected by the objects and received by receiver. The frequency offset between receiving signal (Rx Sig.) and transmitting signal (Tx Sig.) brings the information of range and speed of the objects.

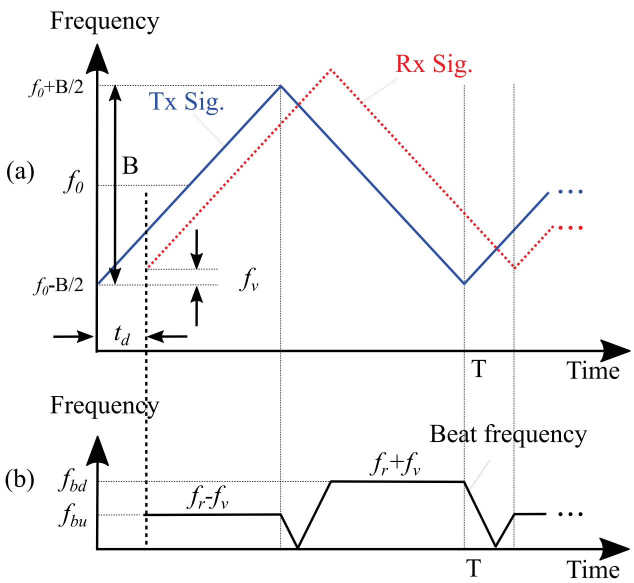

Fig. 2. Classic FMCW modulation (a) Transmitted signal (Tx Sig.) and received signal (Rx Sig.); (b) Beat frequency.

where the symbols are:

T = Modulation period of the chirp;

B = Frequency sweep bandwidth;

f_0 = Center frequency of the transmitted signal;

f_v = Doppler frequency shift;

f_r = Range frequency shift;

$f_{bu} = f_r - f_v$ = The beat frequency for the up ramp;

$f_{bd} = f_r + f_v$ = The beat frequency for the down ramp;

The value of f_{bu} and f_{bd} are calculated through sampled down-converted receive signal. Then, the range and velocity of the object can be reached by following equations:

$$R = \left(\frac{c \cdot T}{4 \cdot B}\right)\left(\frac{f_{bu} + f_{bd}}{2}\right) \quad (1)$$

$$v = \left(\frac{c}{2 \cdot f_0}\right)\left(\frac{f_{bu} - f_{bd}}{2}\right) \quad (2)$$

where R = Range of the object;

v = Relative velocity of the object;

c = velocity of the light;

3 Fast chirp FMCW modulation

3.1 Fast chip FMCW modulation

The Classic FMCW modulation in automotive application usually takes single chirp modulation time as 1 to 10 ms.

$$f_r = \left(\frac{2R}{c}\right)\left(\frac{2B}{T}\right) \quad (3)$$

$$f_v = \frac{v}{c} \cdot f_0 \quad (4)$$

here we set the value:
B=1GHz;
f_0 =76.5GHz;
T=2ms;
Both range frequency shift (f_r) and Doppler frequency shift (f_v) fall in kHz range. It is the flicker noise range of the active devices. It limits the range resolution for the FMCW radar in automotive application. Recently, fast chirp modulation is getting more and more attractions to improve the performance of FMCW radar in automotive applications [7]-[8]. The major advantage is the range resolution improvement.
Fig. 3 shows the principle of fast chirp FMCW scheme. The sawtooth wave modulation is implemented in fast chirp FMCW scheme. The f_r in equ. (3) should be modified as (5):

$$f_r = \left(\frac{2R}{c}\right)\left(\frac{B}{T_{chirp}}\right) \quad (5)$$

The modulation time (T_{chirp}) is about to below 100 µs. In this way, according to equ. (5), the range frequency shift (f_r) is much larger than Doppler frequency shift (f_v). Here we assume the same bandwidth B=1GHz.

The Doppler shift effects are not included in the figure 3. In principle, f_v is independent to the chirp modulation time.

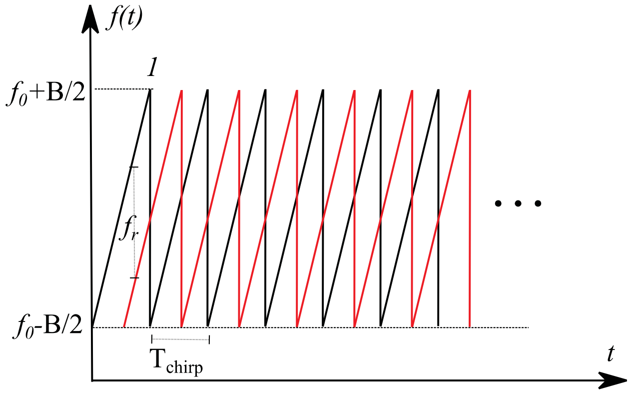

Fig. 3. Fast chirp modulation

In order to analysis the range resolution improvement, we need analysis the phase noise of active devices. Fig. 4 shows the phase noise characteristics of VCO (Voltage Controlled Oscillator). The phase noise is strong in lower frequency offset range (few kHz) while dropped dramatically in higher frequency offset (>1MHz) [2][9-10].

The fast chirp modulation separates the range frequency shift (f_r) and Doppler frequency shift (f_v) in high frequency range and low frequency range. Compare to classic FMCW radar, it increases the range frequency shift while keeping Doppler frequency shift as same as before. Therefore, range and speed of the target may be separated by single chirp modulation period. Furthermore, fast chirp modulation shifts the phase noise of VCO away from the flicker noise dominate and largely reduced the phase noise for the radar system. In this way, the range resolution is improved without degrading the velocity resolution.

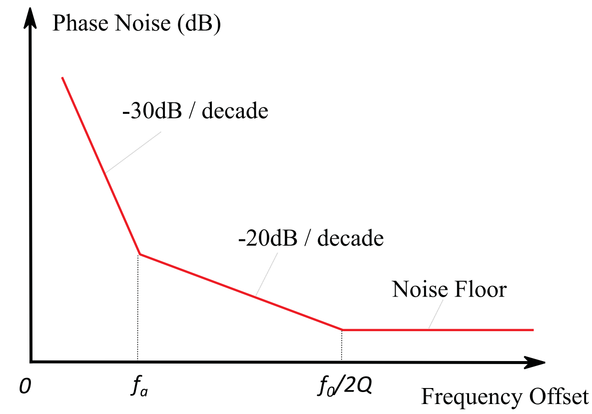

Fig. 4. Oscillator phase noise characteristics.

3.2 Open loop radar concept

Fast chirp modulation requires short chirp modulation time. In automotive application; T_{chirp} is typical required to be less than 100 µs. With classic VCO (Voltage Controlled Oscillator) + PLL (phase locked loop) configuration, it is difficult to reach the required speed [10]. Therefore, open loop concept is implemented in the radar system.

An open-loop radar system is shown in Fig. 4. In such systems, a phase-locked loop is not required to generate linear chirps (FMCW modulation). This approach lowers the total system power consumption. And more important, this configuration releases the acquisition time from PLL. Therefore, the open-loop concept is typically used in combination with a fast chirp FMCW modulation with a chirp time in the range from 10 µs to 100 µs. Furthermore, fast chirp systems lower the duty-cycle and improve the SNR (signal-to-noise ratio) of a radar system because a full radar image is captured quicker.

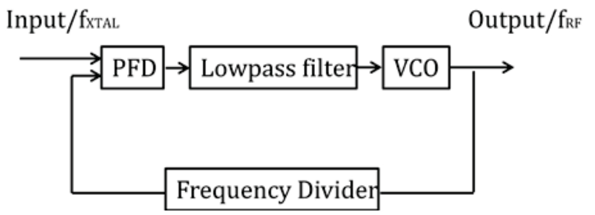

Fig. 5a. Phase lock loop schematic

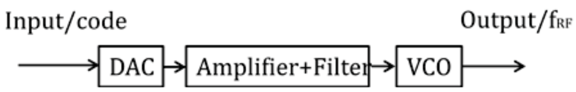

Fig. 5b. Open loop schematic

3.3 Signal processing for fast chirp FMCW

The signal processing procedures are different to the classic FMCW. In fast FMCW radar systems, f_r is much larger than f_v ($f_r >> f_v$), therefore, the beat frequency (f_{beat}) is mainly decided by f_r. f_v may be eliminated from f_{beat} without degrade the resolution for range calculation. Fig. 6 shows a simple configuration of the calculation. The down-converted receive signals are sampled by high speed ADC (analog-to-digital converter). Then f_{beat} is calculated by one dimension FFT (fast fourier transform). The range of the object ("R") may be calculated from equ. (5), where $f_r = f_{beat}$. Since T_{chirp} is largely reduced, a high speed ADC is required in the system.

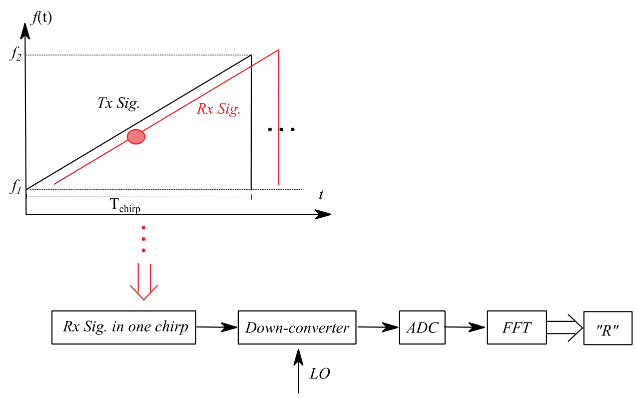

Fig. 6. Signal processing of range calculation

The Doppler frequency f_v is embedded inside the phase information of the receive echo signal $s(t)$:

$$s(t) = F(f_{\text{beat}} \cdot t + \theta)$$

The calculation of f_v requires sampled echo signal in consequence chirp. This needs a second dimension FFT. More detailed signal processing procedure may be referenced from [11-13].

4 A practical system

In this section, we present a practical system in Fig. 5. MR2001 chip set include three different chips, a 4-channel VCO, a 2-channel Transmitter and a 3-channel Receiver. A typical configuration, with MCU (microcontroller), is shown below.

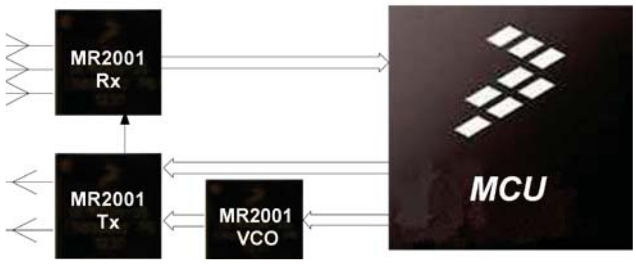

Fig. 7. A practical radar system with MR2001 77 GHz Radar chip set.

The whole system runs fast chirp FMCW modulation with open loop configuration. It supports a couple of advantages over conventional FMCW. First of all, it requires less power consumption because it allows short operational duty cycle. Secondly, it supports better target separation by running IF signal in lower 1/*f* phase noise range. The chirp time of fast chirp modulation typically ranges less than 100µs. It is a few percent of the modulation time of conventional FWCW automotive Radar. It is difficult to realize such short period of PLL with conventional semiconductor technology. Open loop configuration eliminates the limitation of PLL, but a high speed ADC is required. The advanced MCU support high speed data interface and enhanced signal processing function blocks. This can improve the whole radar system performance.

5 Conclusion and further work

This paper demonstrates the principle of the fast modulation FMCW and its application in automotive applications. We also show a practical system with open loop configuration. In the further work, the high linearity system with advanced PLL will be developed with high performance SiGe BiCMOS technology. This may further improve the range resolution of the radar performance [14].

6 Acknowledgement

The authors would like to thank Mr. Maik Brett and Dr. Arnaud Sion for helpful discussion.

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