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Compact X-band FMCW Sensor Module for Fast and Accurate Vehicle Occupancy Detection

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***Abstract* – This paper presents an X-band FMCW sensor module for vehicle occupancy detection with compact size of only 4.5 cm x 4 cm. The transmitting and receiving antenna arrays are co-designed with the sensor to achieve optimal RF performances using less circuit area. Measurement results demonstrate successful and accurate identification of vehicles with fast response time less than 0.5 second.**

***Index Terms* — FMCW radar, Radio wave detector, Sensor, X-band.**

I. INTRODUCTION

Radio sensors based on frequency-modulated continuous-wave (FMCW) detection principles have been commercially developed for measuring the distance and speed of moving targets for many years [1]-[4]. Compared with other ranging methods like pulse radars, FMCW systems are relatively simple and inexpensive to offer high resolution data over wide bandwidths. However, currently available FMCW sensors have bulky sizes and require much time to compute the precise range information [1]-[2]. Thus small form-factor sensors that can fast and accurately detect remote targets are attractive and useful in various commercial purposes such as vehicle occupancy detection [3].

In this paper, a compact X-band FMCW sensor module is designed and implemented. Dual-antenna architecture is used to relieve the stringent requirements of circuit leakages. The transmitting and receiving antenna arrays are two-element patches co-designed with the RF circuits to miniaturize the sensor. With merely a 4.5 cm x 4 cm size of the RF module, the system can identify the incoming of a vehicle and its distance quickly within 2% range error.

II. FMCW SENSOR DESIGN

The simplified system block diagram of the proposed compact FMCW sensor module is shown in Fig. 1. The transmitter consists of a signal generating unit and power divider to simultaneously drive the transmitting antenna array and the receiver. The reflected signal received by a patch antenna array is filtered by a coupled-line RF band-pass filter before fed into the RF receiver. The residual RF noise components are removed by a baseband passive low-pass filter. Then, the filtered baseband signal is amplified and analyzed by a low-power TI digital signal processor to identify the distance and movement of the vehicle targets.

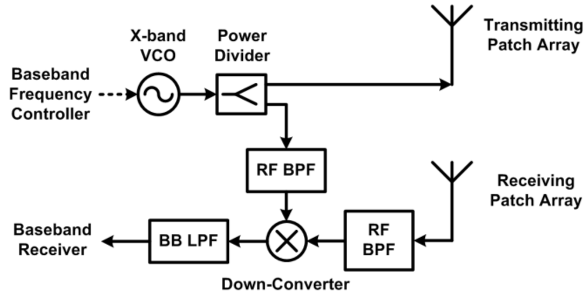


Fig. 1. Simplified system block diagram of the proposed compact FMCW sensor with co-designed T/R antenna arrays.

Both the frequency control and the baseband received signals must be properly isolated to prevent the signal-to-noise ratio degradation due to the coupling interference.

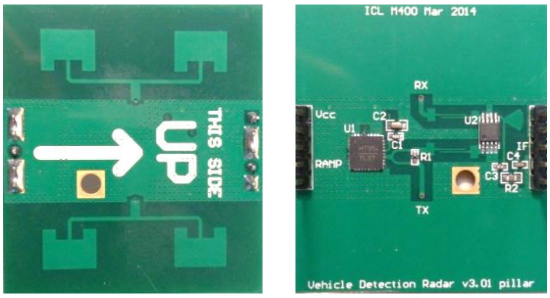
The X-band signal generating unit is the HMC735 VCO manufactured by Hittite Co. with good frequency modulation linearity in the active control voltage range. The output power is 17 dBm, capable of driving both the transmitting antenna array and the receiver. The single-sideband phase noise is -100 dBc/Hz at a frequency offset of 100 kHz.

The RF down-converter is the HMC220 passive mixer also manufactured by Hittite Co. with a moderately flat conversion loss in the FM bandwidth. With 10 dBm local driven power, the conversion loss is nominally 8 dB. The isolations between the RF, IF and LO ports are greater than 15 dB to suppress the dc offsets at the IF output.

The supply voltage of the RF sensor module is 5 V, and the power consumption in consecutive operation mode is 600 mW. While the module is practically operated in the pulsed FMCW mode with a maximum duty cycle of 45 %, the average power consumption can be reduced to less than 270 mW. Thus the thermal issue is also alleviated.

The sensor circuits and the antennas are co-designed and implemented on a 4-metal-layer FR4 board with 1.4 mm thickness. It is noted that the FR4 has a larger substrate loss in X-band, however it is applied to reduce the module manufacturing cost with acceptable RF performances by designing the circuits on the bottom two metal layers. For evaluation, the on-board power divider has an additional 0.3 dB and the matched band-pass filter has 0.4 dB insertion losses compared to the simulated results using the Rogers Duroid 4003 microwave substrate.

To avoid the electromagnetic interference, the sensor circuit and the antennas are placed on different sides of the



(a) (b)

Fig. 2. Photographs from (a) front and (b) back sides of the proposed sensor.

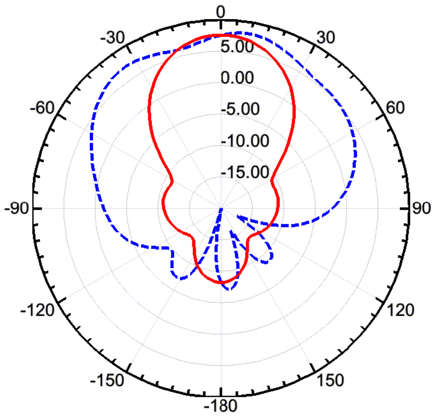


Fig. 3. Radiation patterns of the proposed FMCW sensor module. Red solid line: H-plane. Blue dashed line: E-plane.

printed circuit board. Fig. 2 shows the photographs of the antennas and the circuits of the proposed sensor from the front and the back sides, respectively. The size is only 4.5 cm x 4 cm. The transmitting and receiving linear antenna arrays both have 8 dBi gain and consist of two inset-fed rectangular patches fabricated using full substrate thickness to achieve larger bandwidth up to 870 MHz at 10.5 GHz center frequency. The input impedances of the patch antennas are not matched to 50 ohms but co-designed with the feeding structures and transition vias for optimal radiation efficiency.

The broadside radiation patterns have the beamwidths of 45 degrees in the H-plane and 80 degrees in the E-plane, as shown in Fig. 3. There is a slight main beam fluctuation in the E-plane because the ground plane between the transmitting and receiving antenna arrays behaves as electrically large metallic reflector. Nevertheless, it is tolerable in practical deployments of the sensor modules.

III. Measurement Results

The fabricated sensor module is tested in an open environment. For fast vehicle occupancy detection, pulsed FMCW waveforms are generated with a repetition period of 5 ms. The radiated FM spectrum is adjustable and determined by the baseband frequency controller for different scenarios. Nine pulsed FMCW signals are illuminated on the target but the first two received signals are dropped out to eliminate the transient noises. The sampled baseband signal is analyzed to quickly determine the distance and movement of the vehicle object by short-time Fourier transform.

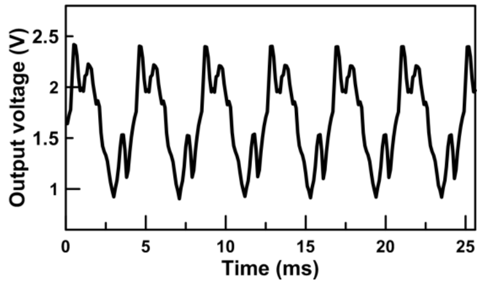


Fig. 4. Measured time domain waveform of the proposed sensor.

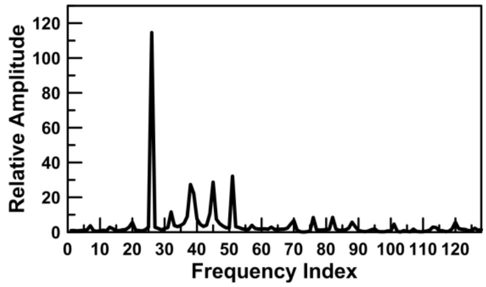


Fig. 5. Measured frequency spectrum of the proposed sensor.

The measured time-domain baseband output waveform and the corresponding frequency spectrum are shown in Fig. 4 and Fig. 5, respectively. The prominent peak indicates the vehicle presents in front of the sensor module at a specified distance. The error of the measured distance is less than 2 %. Thus the proposed sensor has an accurate and reliable detection performance since the response time necessary to identify the occupancy of the vehicles is less than 0.5 second.

IV. Conclusion

Compact FMCW sensor module has been proposed for fast and accurate vehicle occupancy detection. The transmitting and receiving antenna arrays are co-designed with the FMCW sensor module to achieve optimal RF performance in small circuit area. Miniaturized size of the implemented RF module is promising in various applications.

References

[1] V. Winkler, "Range Doppler detection for automotive FMCW radars," in *Proc. 37th European Microw. Conf.*, 2007, Munich, Germany, pp. 1445–1448.

[2] Z. Li and Ke Wu, "24 GHz radar front-end for FMCW and spread spectrum radar applications," in *Int. Microw. Symp. Dig.*, 2006, San Francisco, CA, USA, pp. 351–354.

[3] A. Tessmann, S. Kudszus, T. Feltgen, M. Riessle, C. Sklarczyk, and W. H. Haydl, "Compact single-chip W-band FMCW radar modules for commercial high-resolution sensor applications," *IEEE Trans. Microw. Theory Tech.*, vol. 50, pp. 2995–3001, Dec. 2002.

[4] G. Wang, C. Gu, T. Inoue, and C. Li, "Hybrid FMCW-interferometry radar system in the 5.8 GHz ISM band for indoor precise position and motion detection," in *Int. Microw. Symp. Dig.*, 2013, Seattle, WA, USA.