A Low-Cost 24GHz Doppler Radar Sensor for Traffic Monitoring Implemented in Standard Discrete-Component Technology

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***Abstract*— This paper deals with both the implementation and the real-life characterization of a low-cost 24GHz Doppler radar sensor, purposely designed for the traffic monitoring. To reduce industrial costs as much as possible a discrete-components technology has been adopted for the microwave front-end. Plastic packaged devices and fiberglass reinforced substrate are used in such a way as to fit with standard PCB manufacturing processes and automated assembly procedures. The signal manipulation is based on a state-machine algorithm and has been implemented in a 8051 family micro-controller unit. The realized sensor has a typical output power of 6dBm and mounts a planar antenna with a 3dB beam-width of ±4.5 degrees. The real-life measured performances shows a detection range in excess of 300 meters.**

***Index Terms*— Doppler radar, road traffic control, microwave circuits, velocity measurement.**

I. Introduction

The fast growing of highways and roadways traffic congestion is resulting in an increasing number of car accidents. This calls for a higher traffic control efficiency, since increased driver safety is getting paramount importance. As a response, the transportation industry has focussed its efforts in developing a number of active and passive systems in order to enhance the traffic control, monitoring and optimizing traffic flow in urban and sub-urban areas, thus realizing a sort of intelligent road.

Exploiting a Doppler radar sensor is a good compromise between simplicity, robustness and good performances. It can easily measure both vehicles true-ground speed and vehicle length, thus monitoring a high density traffic road.

The ISM 24GHz frequency band has been devoted, together with other applications, to these services, although the use of lower millimetre-wave band still suffers from high design and production costs, [1].

This paper describes both development and characterization of a 24GHz Doppler radar sensor, purposely conceived for traffic monitoring applications, [2]. The following sections will underline the techniques adopted to minimize the industrial costs of the microwave front-end by a proper selection of technological choices and design options. Finally, an experimental characterization is also reported, describing the Doppler radar sensor performances both in velocity-measurement and length-measurements operational modes.

The result is a very compact, simple and quite inexpensive system, showing state-of-the-art performances, so thus being a good competitor in the traffic monitoring applications market.

II. Sensor Description

The realized Doppler radar sensor (see Fig. 1) is based on the well-know quadrature receiver architecture, necessary to detect the versus of the motion, [3].

A two antennas configuration, one for the transmitter (TX) and one for the receiver (RX) has been adopted in order to avoid the circulator, thus reducing the overall sensor cost. Each antenna is a patch array composed by 10x4 elements featuring a gain of about 13dB and a beam-width of ±4.5 degrees. These antennas have been designed with the parallel loaded, step-impedance weighting approach reported in [4].

The continuous 24GHz waveform is generated by a single-chip commercial VCO with an integrated (divide by 16) prescaler. The VCO output power is about +10dBm with a phase noise of -70dBc/Hz at 10kHz offset from the carrier. A Wilkinson power divider (1dB loss) splits such a signal in two equal parts, one feeding the transmitting antenna and another the receiving channel. The local oscillator signals needed by the I/Q mixers are then derived using a 90 degrees branch-line junction (0.5dB loss). Note that only one source is used to derive both transmitted and local oscillator signals: as demonstrated in [5] this is the key to detect small Doppler shifts even in the presence of phase-noise.

The signal reflected back by the target, and containing the information about the radial velocity of the target itself, is first amplified by a LNA, then divided in two parts and, finally, addressed to the RF ports of the down-conversion I/Q mixers.

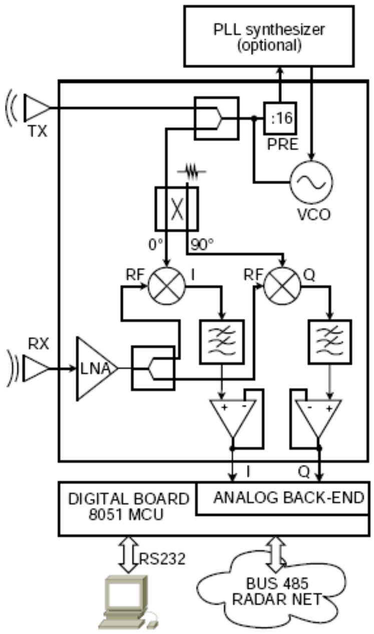

Fig. 1 Block diagram of the realized 24GHz Doppler radar sensor: the I/Q mixer is adopted to discriminate the motion direction.

The low-noise amplifier uses a plastic packaged Hetro-Junction FET and is characterized by a linear gain of 10dB, an input return loss of -15dB and a noise-figure of 1.5dB. The comparison between circuit simulations and measured performances of the LNA is reported in Fig. 2.

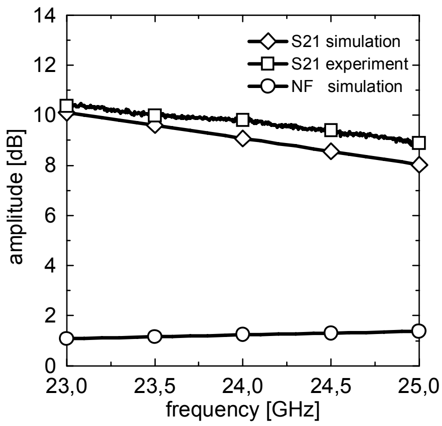

Fig. 2 Small-signal gain and noise figure of the 24GHz low-noise amplifier; comparison between measurement and circuit simulations.

The I/Q mixers have been designed exploiting a single-balanced configuration based on the microstrip 180 degrees rat-race junction, [6]. To save substrate area, the two diodes and the relevant radial stubs have been placed within the ring, leading to a very compact layout. A 5.5dB state-of-the-art conversion loss has been achieved at 24GHz exploiting low-barrier Schottky diodes and properly matching both LO and RF ports. The LO power to optimally driving the mixer is about +1dBm.

The IF signals of the I/Q mixers constitute the outputs of the front-end module. These signals enter a mixed-signal board for the baseband analog amplification (80dB typical) and digital processing. An 8051 family MCU manages both real-time detection algorithm and interfacing procedures.

III. Technologies & Design

In order to reduce the industrial costs of the Doppler sensor as much as possible, some basic technology choices have been assumed as constraints during the design process.

As a first point, a discrete-component technology based on packaged SMT devices, has been adopted in all the active circuitry of the front-end. In this way an automated pick and place process can be used for the board assembly, with the advantages of low production costs.

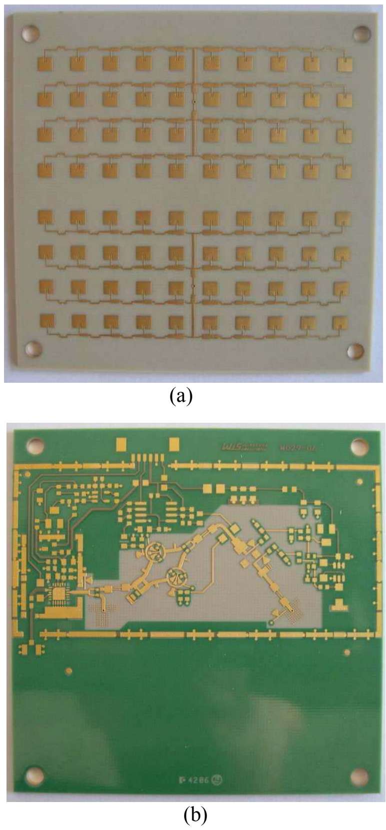

Fig. 3 Photograph of the realized multi-layer 24GHz PCB: (a) antennas side; (b) microwave front-end side.

The second point is the choice of a fiberglass reinforced microwave substrate, along with a multi-layer technology. The cost of this kind of substrates, indeed, is less than that of PTFE materials, moreover they can be easily inserted in a consumer fabrication process, typically tuned for FR4 substrates. From the manufacturing point of view, the main advantage of fiberglass materials is a high finishing quality of the drilled-holes and a superior yield in realizing multi-layer structures.

As a result (see Fig. 3) a complete integration between antenna and microwave front-end has been achieved. These two circuits share the same ground plane. For each of the two antennas the feeding point is connected to the front-end by means of a via-through transition that crosses the ground plane. The latter has been properly discharged and the size of such a ground-plane opening has been exploited as a design parameter to match the via-trough transition. Experimental results of the antenna connected to such a transition show a return-loss better than -16dB.

The final circuit does not needs for any tuning operation, thus saving the corresponding production costs. It can be interfaced to both a personal computer via RS232 serial connection, or to a radar network by means of a IEEE 485 bus. The current consumption of the whole sensor (microwave front-end and mixed-signal processing unit) is about 100mA at 12V supply.

IV. Results

This section describes the results obtained during the real-life characterization of the 24GHz Doppler radar sensor in both velocity-measurement and length-measurement operational modes. All the presented results have been obtained from the same measurement site: a straight road segment about 400m long in sub-urban area, with a road cross at both ends.

A. *Velocity-measurement mode*

The velocity-measurement mode is the basic operational mode of the Doppler radar, and is used to determine the velocity of any objects moving toward the sensor. In this case the antenna beam is pointed in such a way as to be parallel to the road direction, as shown in Fig. 4.

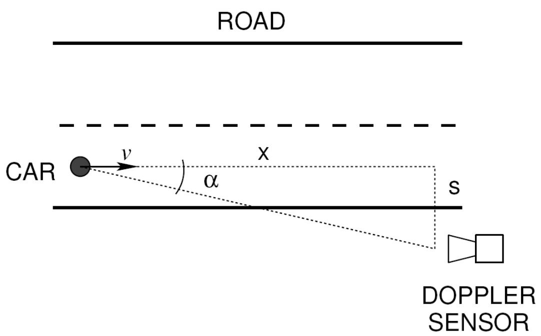

Fig. 4 Experimental set-up adopted during the real-life characterization of the 24GHz Doppler radar sensor in the velocity-measurement mode.

According to the well-known Doppler effect, the frequency shift measured in tracking mode - f_D - is proportional to the radial velocity of the target v_ρ:

$$f_D = \frac{2f_0}{c_0} \cdot v_\rho \tag{1}$$

In this equation f_0 is the carrier frequency of the continuous wave transmitted signal and c_0 is the velocity of the light in a vacuum. For $f_0 = 24$GHz the first factor of (1) assumes the constant value of about 160Hz per m/s or, equivalently, 44Hz per km/h. The radial velocity v_ρ is related to the true object velocity by elementary trigonometrics:

$$v_\rho = v \cdot \cos\alpha \tag{2}$$

where α is the angle formed by the line connecting moving object and radar sensor with respect to the road axis. This angle is time dependent since, as the object travels toward the sensor, the distance x is reduced while the offset S remains constant (see Fig. 4). With the above model, the true object velocity can be retrieved combining (1) and (2):

$$v = \frac{c_0}{2f_0 \cos\alpha} \cdot f_D \tag{3}$$

Assuming a 5% maximum tolerable discrepancy between v_ρ and v, i.e. $\cos\alpha = 0.95$, one obtains that the radar readout is acceptable until x is reduced down to about $3S$. In the real practice S is less than 5m and v_ρ can be assumed equal to v until the distance between moving object and sensor is greater than about 15m.

A typical velocity measurement result is shown in Fig. 5, where the initial time (0s in the graph) correspond to the begin of the data acquisition, i.e. to the maximum distance between moving object and the radar sensor. The car under observation was a FIAT Panda and is velocity vary with time in according with true acceleration and deceleration of the car itself.

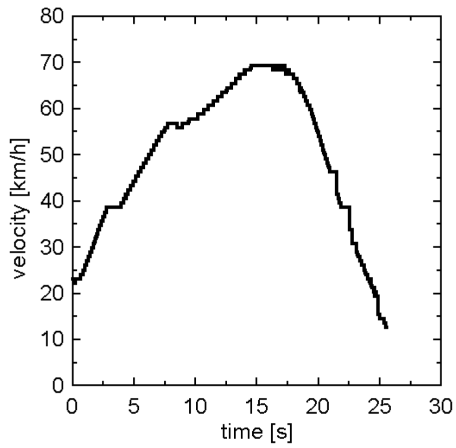

Fig. 5 Measured velocity in km/s as a function of time: t=0s indicate the time instant when the car has been seen by the doppler radar sensor.

The steps in the ascending ramp correspond to the transition between second to third gear and third to fourth gear and have been correctly detected by the sensor. From the analysis of this figure one can clearly see that the 50km/h velocity limit has been surpassed: this information can be used to activate a warning display placed along the road.

Once the velocity has been measured with respect to time it is possible to numerically integrate (post-processing) the motion equation in such a way as to obtain the distance x:

$$x(t) = \int_0^t v(\tau) \cdot d\tau - \int_0^{t_F} v(\tau) \cdot d\tau \tag{4}$$

Fig. 6 is obtained applying (4) to the results in Fig. 5 (final time $t_F = 25$s) and eliminating the temporal variable between space $x(t)$ and velocity $v(t)$. A maximum radar detection range of about 350m can be estimated from this figure.

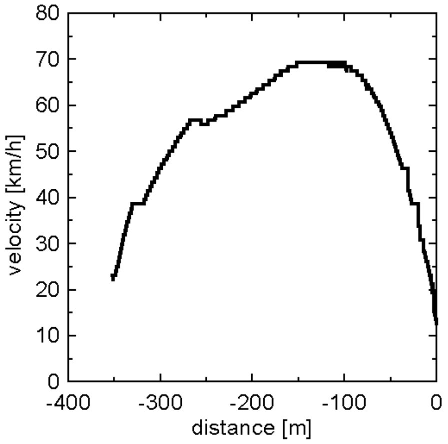

Fig. 6 Measured velocity in km/h as a function of the relative distance between car and radar sensor: the reduction of the velocity in the proximity of the sensor is due to a true deceleration of the car.

B. *Length-measurement mode*

The length-measurement mode is used to determine the length of a moving object crossing the antenna beam as illustrated in Fig. 7. This operational mode is particularly useful in traffic statistics since one can both count the number of vehicles flowing in a certain road and classifying them (i.e. distinguish between car, truck, etc.) from their length, [7].

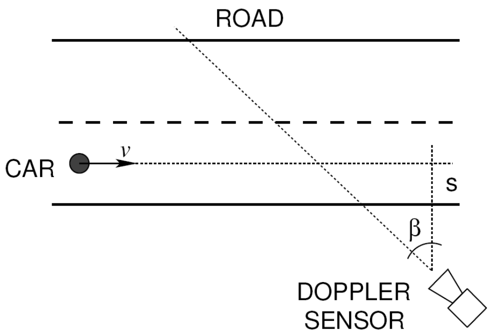

Fig. 7 Experimental set-up adopted during the real-life characterization of the 24GHz Doppler radar sensor in the length-measurement mode.

Let first consider the case of an infinitely narrow antenna beam, i.e. θ_{3dB}=0. The Doppler frequency shift seen by the sensor is related to the set-up pointing angle β:

$$f_D = \frac{2f_0 \sin\beta}{c_0} \cdot v \tag{5}$$

This frequency is directly proportional to the velocity v of the object. On the other hand, the time t_C needed by the same object to cross the antenna beam (slanted line in Fig. 7) is proportional to the length l of the object and inversely proportional to its velocity:

$$t_C = \frac{l}{v} \tag{6}$$

This means that the product between f_D and t_C, i.e. the number N_D of Doppler pulses at the output of the sensor, is independent on velocity and proportional to the object length.

$$N_D = t_C \cdot f_D = \frac{2f_0 \sin\beta}{c_0} \cdot l \tag{7}$$

The relationship (7) can easily be corrected in such a way as to consider a non-zero antenna beamwidth. This has the effect of increasing the apparent object length by a term l_F:

$$l_F = S\tan\left(\beta + \frac{\theta_{3dB}}{2}\right) - S\tan\left(\beta - \frac{\theta_{3dB}}{2}\right) \tag{8}$$

being S the displacement between the radar position and the motion line (see Fig. 7). As a consequence (7) become:

$$N_D = \frac{2f_0 \sin\beta}{c_0} \cdot \left(l + l_F\right) \tag{9}$$

To verify the performances in length-measurement mode, the sensor has been pointed with an angle β=π/4 with respect to the road direction. The displacement S of the sensor was 5m, while the antenna footprint l_F has been estimated in about 1.6m assuming a beamwidth of ±4.5 degrees.

TABLE I
LENGTH-MEASUREMENT EXPERIMENTS

car type	length [m]	N_D		error ε%
		theory	measure	
Volkswagen Golf	4.20	650	665	2.25
Ford Focus	4.49	680	698	2.57

The resuls of this experiment are quoted in Tab. I, showing a very good agreement between the number of Doppler pulses predicted by (9) and those effectively measured by the sensor. In all the cases the reported error is less than 3%.

V. CONCLUSIONS

A low-cost Doppler radar sensor, purposely designed for traffic monitoring applications, has been developed. It uses a discrete-component technology as well as a multi-layer PCB realized with fiber-glass reinforced microwave substrate. The sensor has a typical output power of +6dBm and a current consumption of 100mA at 12V supply (digital unit included). Real-life characterization experiments show a detection range in excess of 300 meters in the velocity-measurement mode and an error less than 3% in the length-measurement mode.

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