Mm-wave front-end developed within the on-going AWARE/LOCOMOTIVE projects for automotive applications at 77GHz

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ABSTRACT

This paper describes the development of a millimetre-wave front-end for a 76.5GHz Collision Warning Avoidance (CW/A) car radar. This CW/A sensor is based on a FMCW concept. The main development steps are described and have led to the definition of a fully MMIC-based front-end. Based on a demonstrator done in AWARE a new chip-set has been defined, fabricated and characterised within LOCOMOTIVE. Using a total chip-set area of 13.7 mm², the first obtained results show a high level of performance.

INTRODUCTION

After more than 20 years of research and development works all around the world, 1998 saw the first commercial introduction of millimetre-wave car radars ; the millimetre-wave front-ends of these radar are manufactured using hybrid assemblies of Gunn, Schottky and PIN diode circuits. However, for a very large availability of this kind of car equipment, whose ultimate goal is to improve the road safety, very low prices are required. In our view, this will be only possible by using a full MMIC solution, which will bring the following advantages :

- a drastic reduction of the need for circuit tuning
- a drastic reduction of the number of components to be assembled
- an overall reduction of the size of the front-end module
- an improved thermal stability
- an improved reliability

Depending on the sensor specification several techniques are used for carrier modulation. Among them the most known are:

- FSK
- FMCW
- Pulsed
- Spread Spectrum

A combination of these techniques can also be used in order to maximise the level of radar performance.
In this paper we report the developments done on FMCW radar front-end in the frame of AWARE/LOCOMOTIVE E.U. projects.

AWARE PROJECT

This project concerns 77GHz radar sensors for automotive Collision Warning Avoidance applications [1]. The main steps are:

- to define the requirements and specifications of the 77GHz radar sensor
- to prove the feasibility by developing a complete sensor based on industrial technologies
- to validate the concept in a car

Front-end architecture definition

After defining a preliminary set of specifications and based on the generic architecture given in fig. 1, a front-end analysis has been done with the main following objectives:

1. the block diagram has to be compatible with fully MMIC-based components even if some of them will be developed after this project.
2. for short term realisation, existing components have to be used

According to these constraints the block diagram shown in fig. 2 has been chosen. It consists of:

- a VCO at 38GHz (based on harmonic generation)
- a transmitter multifunction combining a frequency multiplier and a medium power amplifier with two outputs
- a mixer at 77GHz
- a reference oscillator (also based on harmonic generation) for VCO linearisation purpose
- a mixer at 38GHz providing the IF signal necessary for the linearisation loop

Front-end optimisation and realisation

During the component characterisation phase we detected two main difficulties.
The first one was about the phase noise of a MMIC-based VCO which was chosen at the beginning. This standard MMIC was not able to fulfil the required level of performance. so a hybrid VCO at 19GHz was used. A MMIC-based doubler from 19GHz to 38GHz has been added.
The second difficulty was about the noise figure of the receiver. Indeed the level of low frequency noise of the standard mixer (developed on HEMT process) was too high so it has been necessary to develop a new MMIC mixer using a high quality Schottky diode process (called BES). This BES process allows to integrate in a MMIC format Schottky diodes with very low series resistance, resulting in high performances mixer circuits with very low conversion loss and noise. Based on a balanced structure, this new mixer design has very high LO to RF isolation and LO signal AM noise rejection. A characterisation done in test fixture shows a conversion loss lower than 7.5dB. The optimum IF load is around 200Ω. The IF noise performance of this down-converter allows to reach noise figure in the range of 13dB at 1MHz IF. This IF noise is below -166dBm/Hz at 100kHz and the change from P-HEMT to Schottky diode MMIC technology has allowed to improve this characteristic by more than 15dB.

Based on these improvements the final millimetre-wave front-end uses one hybrid VCO and 5 MMICs.

Several prototypes have been realised. They consist of one metallic package integrating the VCO and the MMICs into a first cavity dedicated to high frequency circuits, and all the low frequency control circuits into a second cavity. For the millimetre wave interconnections low dielectric constant soft substrates were used. A filter was designed and put between the VCO and the transmitter. A special environment (local cavity) was necessary for the reference oscillator as it is stabilised by an external dielectric resonator. Micro-strip to wave-guide transitions were necessary to provide standard WR-10 connections at 77GHz. An external wave-guide circulator, used as duplexer, has been chosen for these prototypes. The interconnections between high and low frequency cavities are done thanks to coaxial feed throughs.

Front-end characterisations

The obtained results are summarised on table 1. The main objectives have been reached: tuning range is more than 0.5GHz (fig. 3), output power is higher than 11dBm (fig. 4), phase noise is better than -60 dBc/Hz at 100kHz from carrier, noise figure is around 18dB at IF=1MHz. Operating temperature range is -30°C to +80°C. The MMIC reference oscillator phase noise and stability are respectively -97dBc/Hz at 100kHz from carrier at 38GHz and lower than 5ppm/°C. The front-end is now under test in a car.

<u>LOCOMOTIVE PROJECT</u>

As the main identified problem during AWARE project was the MMIC-based source performances, the objective of LOCOMOTIVE is the development of an integrated low cost and low phase noise millimetre-wave source for 76.5GHz FMCW radars. The main steps are:

- to define detailed specifications (using AWARE characterisation in a car)
- to perform a specific component characterisation and modelling of low frequency noise
- to develop a cost effective MMIC chip-set
- to validate the design in a car radar

After global front-end analysis, an optimised MMIC partitioning has been defined and led to the architecture given in fig. 5. This chip-set is composed of four MMICs: a 38GHz VCO multifunction (chip 1), a reference oscillator/harmonic mixer multifunction (chip 2), a 76.5GHz power transmitter multifunction (chip 3) and a down-converter circuit (chip 4). The MMIC designs have been done in order to improve the overall front-end performance. The main objectives were:

- to improve the noise performances: FM noise of the VCO and AM noise of the transmitted signal
- to minimise the chip-set size
- to increase the operating temperature range
- to take into account the assembly constraints when automatic tools are used (pick and place, wire bonding ...).

In order to reach the optimum cost / performance trade-off, the chip-set uses three different MMIC processes : the VCO and reference chips at 38GHz are on a 0.25µm P-HEMT process (PH25); the 76.5GHz transmitter circuit uses a 0.135µm P-HEMT process (PH15); the receiver circuit uses a GaAs MMIC Schottky diode process (BES).

The MMIC partitioning minimises the number of bonding wires at 76.5GHz. However, each chip has been designed taking into account specific rules for the wiring parasitic and spread on top of the more conventional technology spread analysis. Specific matching networks are placed on the chip and/or on the external substrate in order to minimise the MMIC to MMIC or MMIC to external substrate transition loss.

Transmitter chip

The power transmitter circuit is composed of a frequency multiplier (converting the input 38GHz signal of the local oscillator circuit to 76GHz) followed by a medium power amplifier. This circuit has a main output and an auxiliary output ; the main output is used to feed the radar antenna ; the auxiliary output is used as the local oscillator input to the down-converter receiver circuit.

After characterisation done in the frame of AWARE project, it has been determined that the amplitude noise (AM) of the transmitter chain (oscillator + transmitter circuits) was a limiting factor for the overall performances of the radar. Indeed, due to the facts that the IF is very low and the receiver is homodyne the noise figure is affected by the AM noise of the transmitted signal.

Taking into account this remark and the increase of the operating temperature range a new version of this chip has been developed and is detailed in [2].

Receiver chip

As this chip has been already optimised and developed during the AWARE project it will be re-used as it is.

VCO multifunction chip

The oscillator circuit is composed of a VCO at 12.75GHz followed by a frequency tripler. Buffer amplifiers at VCO frequency and at 38GHz reduce circuit sensitivity to temperature and spreads. The on-chip varactor is based on HEMT Schottky diode. An external medium Q passive resonator gives the centre frequency, temperature stability and optimum phase noise performance for a given frequency tuning range. This off-chip resonator is based on a micro-strip filter used in transmittive mode. Coupled to this filter, the frequency tuning capability of the free running VCO is shown in Fig. 6, it has been measured in a test-jig at three different temperatures, between -40°C and +100°C. Whatever the temperature more than 200MHz tuning range can be used with a reasonable linearity characteristic. The output power (fig. 7) is higher than 6Bm with less than 1.5dB variation versus the tuning voltage. The phase noise performance is shown in Fig. 8: better than -75dBc/Hz. is obtained at 100kHz from carrier at 38GHz. These results are today among the best ones obtained on P-HEMT process, they allow to propose a complete MMIC solution for the millimetre-wave front-end.

Reference multifunction chip

This multifunction is composed of a high quality fixed frequency oscillator and an harmonic mixer. Buffer amplifiers are also used for performance improvement in all the environmental and spread conditions. Two possibilities have been considered:

- an oscillator around 19GHz and a second order harmonic mixer
- an oscillator around 12.5GHz and a third order harmonic mixer

Each multifunction has been realised. The choice is not yet done, however the first one has a determinant advantage concerning size (cavity for the resonator). Whatever this choice the oscillator has to be coupled to an external high Q resonator (i.e. dielectric resonator) in order to achieve stability and phase noise performances.

Coupled to a dielectric resonator the 19GHz based multifunction has been characterised. The conversion loss, shown in fig. 9), is always between 4 to 8dB whatever the IF and the temperature range (from -40°C to +100°C). Fig. 10 shows the oscillator characteristic versus the temperature: the stability is better than 3ppm/°C, the output power variation (measured thanks to an auxiliary output) is lower than 2dBm in the temperature range. The phase noise of the oscillator, given at 38GHz; is better than -100dBc/Hz at 100kHz from carrier. Without any off-chip filtering, the second LO harmonic leakage at RF port is lower than -40dBm. The LO leakage at IF port is lower than -25dBm.

CONCLUSIONS :

All the work done in the frame of AWARE/LOCOMOTIVE projects has yet demonstrated that for CW/A automotive radars at 77GHz there is an industrial solution to built the millimetre-wave sensors. Indeed, only 4 MMICs allow to obtain all the millimetre-wave requirements for the front-end. Key specifications like tuning range, output power and noise characteristics are obtained within the full required temperature range. The chip set partitioning and the MMIC design which takes into account automatic equipment for inter-connections allow to built a low cost and low size module based on micro-strip approach. The total chip-area is 13.7mm². Future work will consist of applying the results of the low frequency noise characterisation and modelling work done in parallel in order to improve again the final specification and try to reduce the chip-set size.

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- CelsiusTech Electronics (Magnus KAMEL, Ingemar Back, Christian BJORLIN)
- IRCOM (Michel PRIGENT, Juan OBREGON)

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[1] : H. Lind, 'AWARE project',Collision Warning and Avoidance Systems, Advanced Microsystems for Automotive Application, Berlin, March 26-27 1998.

[2] : M. Camiade et al, 'Full MMIC millimetre-wave front-end for a 76.5GHz Adaptative Cruise Control Car Radar' , IEEE MTT-S, Anaheim, 1999. vol. 4.

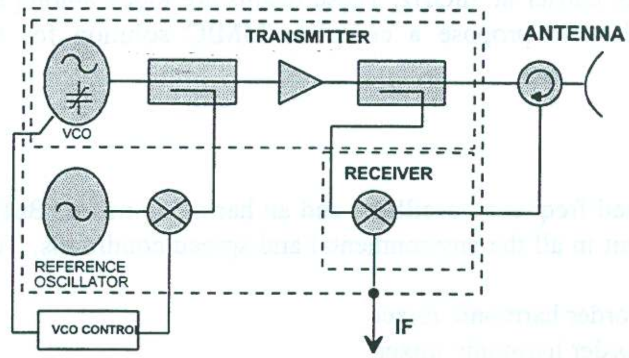

Fig. 1 : Generic block diagram for FMCW CW/A millimetre-wave front-end

Parameter	Objectives			Results	Unit
	Min	Typ.	Max		
Power to the antenna (P)	8	10	16	>11	dBm
Receiver noise figure SSB @ 700 kHz video (NF) (including the IF1 amplifier NF)		16	18	18	dB
Transmitter phase noise (at 100kHz from carrier, at 77GHz)		-60	-57	-62	dBc/Hz
Reference oscillator phase noise (at 100kHz from carrier, at 77GHz)		-90	-87	-91	dBc/Hz
Transmitter AM noise SSB (at 1MHz from carrier, at 77GHz)		-155	-152	-149	dBc/Hz
IF2 (Loop IF2) centre frequency	250	300	350	250-350	MHz
IF2 (Loop IF2) output power (including the IF2 amplifier)			-10	-10	dBm
Transmitting frequency	76.1		76.9	76.1-76.9	GHz
P/NF at 700kHz	-10	-6		-7	dBm

TABLE 1 : Main results obtained on the AWARE millimetre-wave front-end

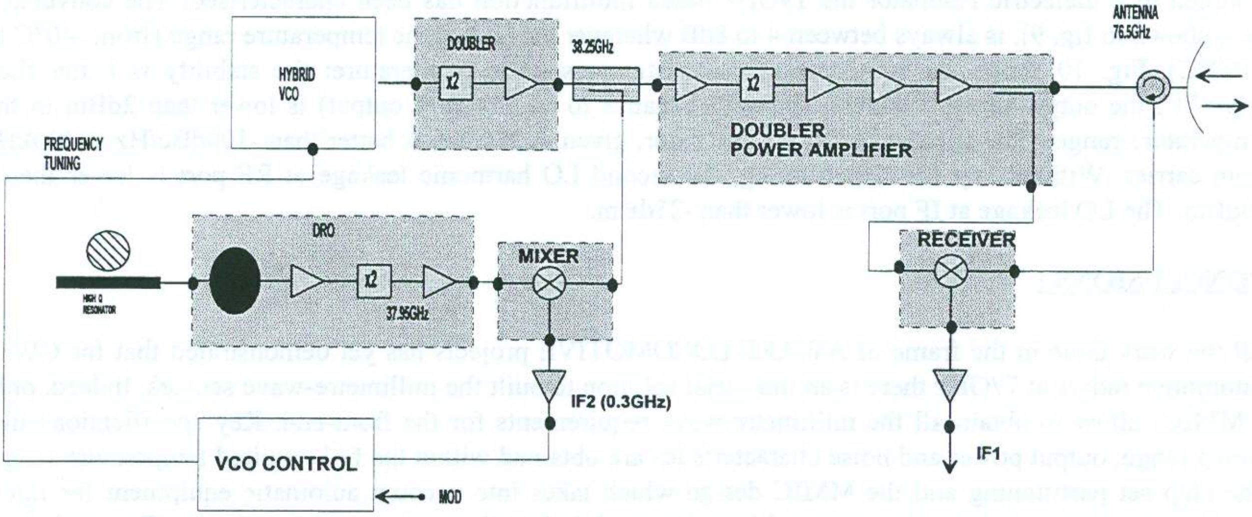

Fig. 2 : Block diagram of the 76.5GHz front-end defined in AWARE project. It was based on existing components. One hybrid VCO and 5 MMICs are used.

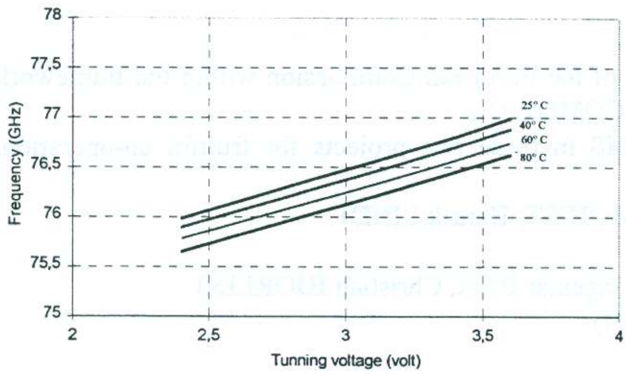

Fig. 3 AWARE front-end : Frequency tuning characteristic

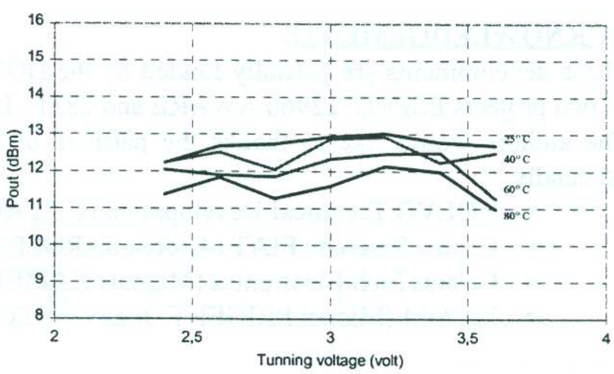

Fig. 4 AWARE front-end : Output power characteristic at 77GHz

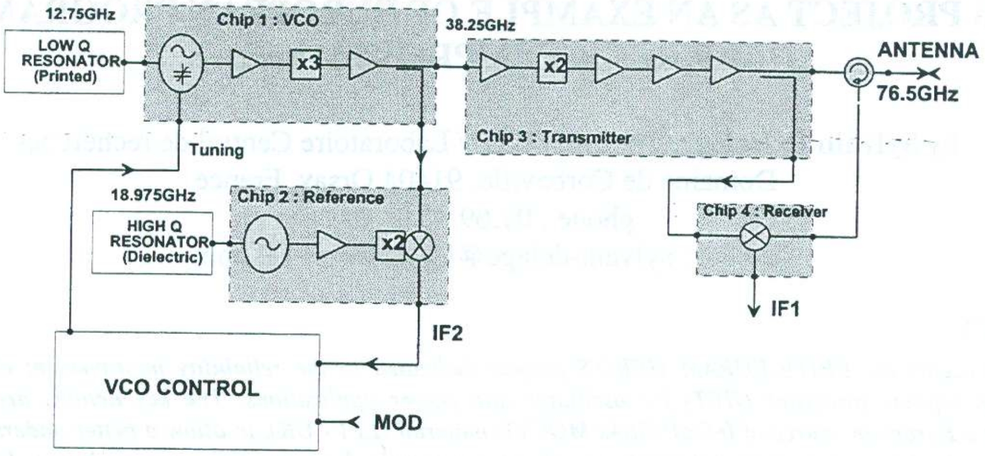

Fig. 5 : Block diagram of the 76.5GHz front-end defined in LOCOMOTIVE project. It is based on 4 MMICs: a VCO at 38GHz, a reference at 38GHz, a transmitter at 77GHz and a mixer at 77GHz.

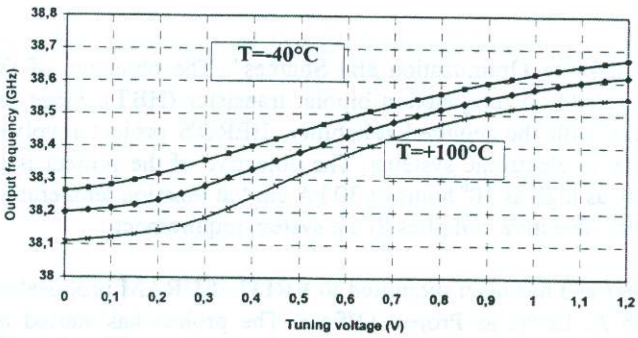

Fig. 6 : Measured performance of the VCO circuit. Frequency versus tuning voltage measured at three different temperatures: -40°C, +25°C and +100°C.

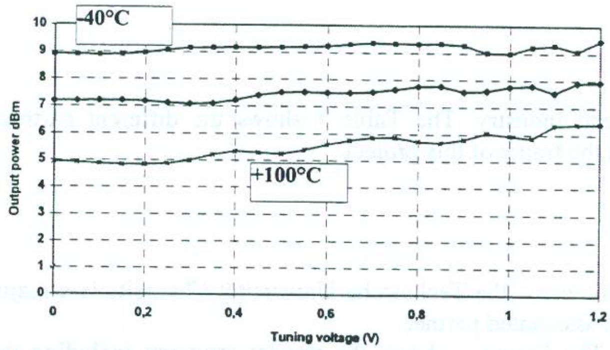

Fig. 7 : Measured performances of the VCO circuit. Output power versus tuning voltage

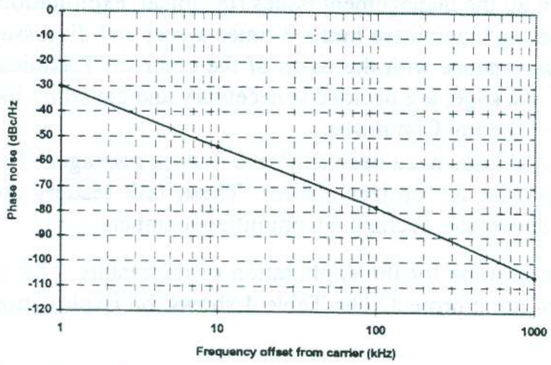

Fig. 8 : Measured performances of the VCO circuit. Phase noise for Vtune=0.6V (T=25°C).

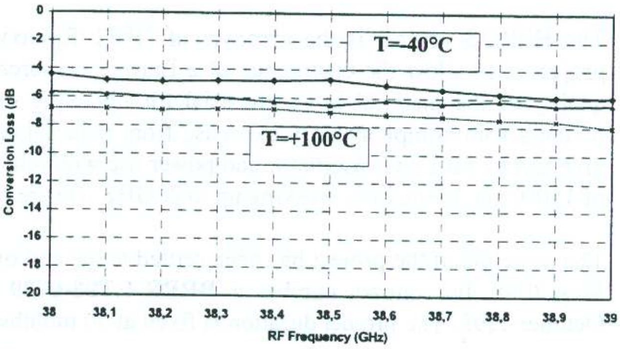

Fig. 9 : Measured performances of the 38GHz reference circuit. Conversion loss versus RF at three temperatures: -40°C, +25°C, +100°C.

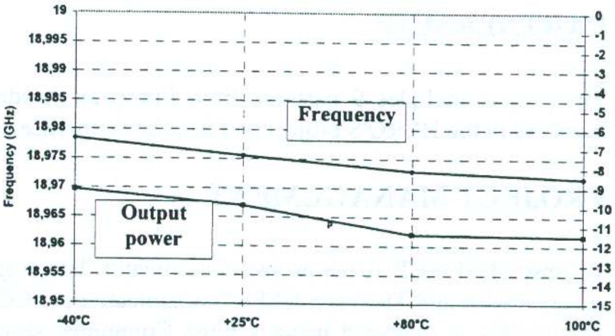

Fig. 10 : Measured performances of the 38GHz reference circuit. oscillator output power and stability versus temperature.