A V band singly balanced diode mixer for space application

C. Florian[1-3], F. Scappaviva[3], M. Feudale[2], V.A. Monaco[1], F. Filicori[1]

[1]DEIS, University of Bologna, Bologna, 40136 Viale Risorgimento 2, Italy, tel. +390512093846,
cflorian@deis.unibo.it, vmonaco@deis.unibo.it, filicori@deis.unibo.it
[2]Alenia Spazio, Roma, 00131 Via Saccomuro 24, Italy, tel. +390641514107, m.feudale@roma.alespazio.it
[3]MEC s.r.l., Bologna, Viale Pepoli 3/2, Italy, tel. +390516440568, corrado.florian@mec-mmic.com,
francesco.scappaviva@mec-mmic.com

Abstract — **The paper describes the design of a V band single balanced mixer to be employed in the front end of an on-board receiver for space applications. The V band receiver is a demonstrator for the use of different monolithic processes and interconnection/assembly technologies in space applications at such high frequencies. The receiver front-end consists of a multi-stage LNA amplification followed by an image reject filter, the mixer and a frequency doubler for the local oscillator. All the chips are mounted over an LTTC substrate using bumps/hot vias technology. Chip to chip interconnection is provided by coplanar wave guide on LTTC. The mixer employs a rat race 180° hybrid to balance the local oscillator and a couple of Schottky diodes as mixing elements. The technology employed is a 0.15µm pHMET process that offers diodes with a cut off frequency higher that 300GHz. The choices made for the mixer type and topology starting from the system specifications are covered in the paper along with the actual description of the circuit design.**

I. INTRODUCTION

A technology demonstrator for different monolithic processes and innovative interconnection and module assembly solutions has been implemented by Alenia Spazio in the framework of an ESA (European Space Agency) program.

An on-board solid state receiver has been designed to operate in the 60-70GHz band. The RF section feeding the mixer is composed of a waveguide to coplanar transition followed by two monolithic LNA amplifiers and an image rejection filter. This section has been optimized to guarantee the required noise figure and to filter out the image of the RF signal.

The technology chosen for the mixer is a 0.15µm pHEMT process that offers also a new interconnecting solution: hot vias and bumps [1] replace the use of wire bonding that presents some drawback at such high frequencies. The module assembly employs an LTTC process [2][3]: the monolithic bare dies are mounted over the LTTC substrate and both die grounding and signal paths are supplied by bumps from the back side of the chip. Hot vias carry signals and reference from the die top to the backside signal pads and ground plate. In this paper the mixer design is described.

II. TECHNOLOGY

The technology for the mixer is the PH15 0.15µm low noise pHEMT process by United Monolithic Semiconductors. For a mixer design this process offers different choices: indeed we could choose between hot FET, cold FET and diode models to design a transconductance FET mixer, a resistive FET mixer or a diode mixer. In addition the process offers 330pF/mm^2 silicon nitride MIM capacitors, air bridges, two levels of interconnect layers, spiral inductors and three types of resistors (TaN, TiWSi, GaAs). Schottky diodes are derived from the FET structure and are designed for low junction capacitance and low series resistance.

The obtained cut off frequencies exceed 300GHz. This type of pHEMT based diode technology has demonstrated its effectiveness for applications at V and W frequencies [4].

III. SPECIFICATIONS AND MIXER TOPOLOGY

The main specifications for the mixer, based on system requirements, are reported in table 1. Starting from these requirements we identified a suitable mixer type and topology. Since there is no need of transducer gain and the power consumption is a main concern for space applications, we chose a diode mixer topology employing unbiased diodes.

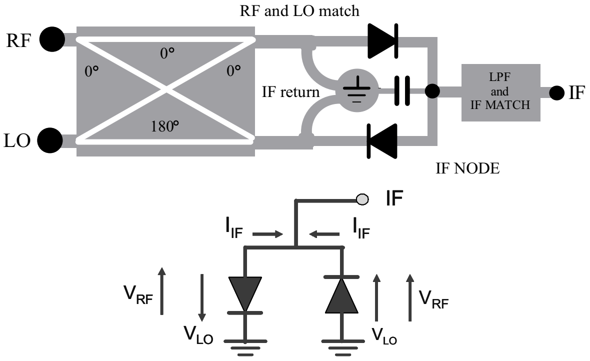

Fig. 1. Block diagram of the designed mixer. LO is balanced by means of a Rat Race hybrid. Microstrip lines provide the LO/RF matching to the diodes along with IF and DC current return paths. A low pass filter extracts the IF from the IF node.

Parameter	Unit	Requirement	Remarks
RF Frequency	GHz	60-70	
IF Frequency	GHz	4 - 14	
LO Frequency	GHz	56	
Insertion Loss	dB	15	
Amplitude Flatness	dBpp	< 2	Over full temperature range -20°C +50°C
RF port Return Loss	dB	> 15	Over full temperature range -20°C +50°C
IF & LO port Return Loss	dB	> 12	Over full temperature range -20°C +50°C
LO Power	dBm	> 10	
Maximum channel temperature	°C	110	@ backside temperature of 70°C
Isolation between all ports	dB	> 15	
LO Harmonics at IF port	dBc	> 20	Except the first harmonic
RF – LO Intermodulation products	dBc	> 20	Only products inside the IF band

TABLE I
MIXER PERFORMANCE REQUIREMENTS

The need to suppress the LO power at the IF port drove to the choice of a balanced topology for the local oscillator. On the other side, from CAD simulations we estimated that the RF to IF isolation required could be achieved by proper filtering at the IF port, hence a balanced structure was not required for the RF signal also. In fact a Rat Race 180° hybrid has been used to implement a singly balanced diode mixer [5]. As shown in figure 1, the LO pump is applied to the hybrid balanced port and drives two identical diodes in anti-phase.

Therefore the LO signal adds destructively at the IF node (figure 1), and a high LO isolation can be achieved: indeed the only source of unbalance in this topology is the asymmetrical diodes orientation.

Differently from the LO, the RF signal is carried in phase at the diodes. The mixing effect is due to the multiplication of the time-varying diodes conductance $g(t)$ (modulated by the LO), and the RF signal $v(t)$.

Since the diodes are reversed (figure 1), the small-signal IF currents $i(t)=g(t)v(t)$ add in phase at the IF node and can be extracted with a low pass filter [6]. If there is enough power from the LO and a good LO matching is provided, the diodes can also be unbiased.

As depicted in figure 1, a distributed matching is provided to the diodes for the RF and LO frequency by means of microstrip lines: in this structure two lines provide the return path for the IF and the DC currents of the diodes to ground [6].

A lumped capacitor is placed between the IF node and ground to short-circuit the RF signal at that point and to inhibit RF leakage through the IF port. Since the LO signal is quite close to the RF one, that capacitor acts as a LO to IF leakage suppressor also (in addition to the mixer symmetry that balances the LO port).

Beyond balancing the LO signal, this topology has the nice property to suppress all the mixing products mRF±nRF where m is even [7]. For instance when RF=60GHz and LO=56GHz, the spurious product 2RF-LO is at 8GHz and would fall inside the IF band.

The Rat Race configuration offers typically a 15% bandwidth and can be used when the IF value is roughly to 15% of the RF/LO center frequency [8]: as can be appreciated in table 1, those characteristics fit perfectly to our specifications.

IV. MIXER DESIGN AND PERFORMANCES

The first step to design the mixer is the choice of the diodes: 2 fingers per 5μm devices were selected to guarantee a good trade off between input impedence, LO drive needed and diode conductance.

As shown in figure 2, the Rat Race exhibits elongated shape to optimize the space utilization. Indeed, we chose to put the diodes inside the hybrid to save area and to use a single central via hole to ground both diodes [9]. This choice is very efficient in terms of compactness, but imposes tight geometric constraints in the synthesis of the matching networks to the diodes.

We used a 0.2pF lumped capacitor to ground the IF node for RF and preventing RF leakage to the IF port. Since the resonant frequency of this capacitor is between 50 and 60 GHz, an electromagnetic simulation was used rather than the electrical model.

The combination of this capacitor and the IF low-pass filter guarantees more than 30dB of RF to IF isolation, even though the mixer is not balanced for the RF.

The IF low-pass filter is synthesized with a high impedence line, a first radial stub to ground residual RF/LO and a second stub to short-circuit the LO second harmonic.

With this mixer topology the IF filter crosses the Rat Race hybrid with an air bridge, which has been accurately electromagnetically simulated.

The estimation of the isolation properties of the air bridge is very important because a cross talking at that point would considerably degrade the RF to IF and LO to IF isolation performances.

The combination of the balanced symmetrical structure and the IF low-pass filter has a very strong effect for the LO power suppression at the IF port. Indeed 50dB LO-to-IF suppression is foreseen by simulations, which take into account both the air bridge residual coupling and the diodes asymmetry.

In figure 3 the voltage drop at the diodes terminals and their currents are depicted: it is put in evidence the weak difference between the two devices working condition, due to the asymmetry of their terminals (figure 4) and the antipodal connection (figure 1).

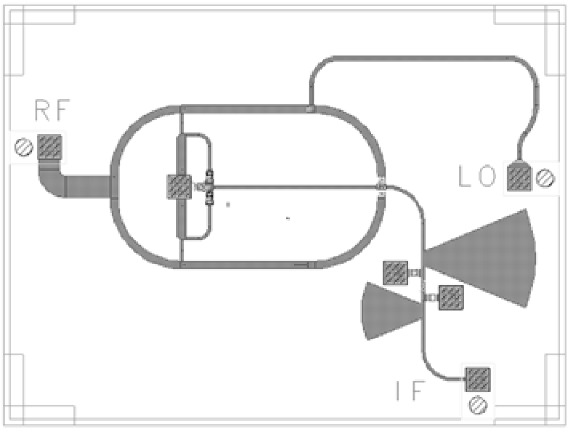

Fig. 2. Layout of the designed singly balanced Rat Race diode mixer. As seen in the layout no bias is needed for the diodes.

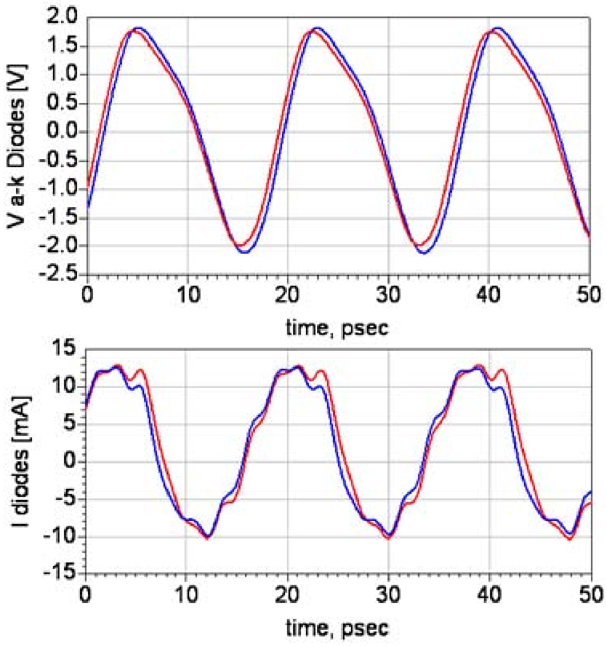

Fig. 3. Anode-cathode voltages and currents of the two diodes: the symmetry of the circuit is a fundamental property.

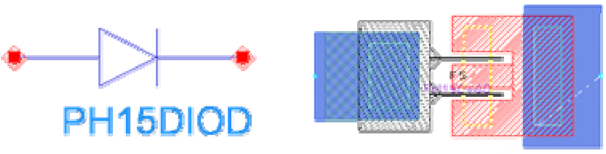

Fig. 4. Two fingers per 5um diode layout.

A challenging specification is represented by the IF return loss over the bandwidth. To match this requirement it is possible to choose between the use of a buffer stage as separator or a passive attenuator. Since we had a good margin for the insertion loss, we chose to put a π resistive 3dB attenuator at the IF port between the two stubs: obviously this is a good choice in terms of complexity, space, reliability and power consumption with respect to an active buffer stage.

As far as regarding the maximum channel temperature for the diodes, the temperature increase from the backside is almost negligible since the diodes are unbiased and the power dissipation is very low.

One of the most tricky and time-demanding aspect of the design is obviously the high operating frequency.

At V band the dispersive phenomena associated to the non ideal semi insulating substrate are quite important and electromagnetic simulations of the microstrip structures are mandatory.

In addition to this consideration even the presence of a protective BCB coating over the entire chip needs to be taken into account during EM simulation, since it has a sensible effect at V band.

Another important issue related to the very high operation frequency is associated to the design sensitivity respect to the MMIC transitions. Indeed, as mentioned before, this application exploits a hot vias-bump transition to carry the signal from the chip to the receiver module coplanar lines. The return losses at each port depicted in figure 7 are obtained using an equivalent circuit model for the hot via-bumps transition: this matching is quite sensitive to the transition characteristics; hence an accurate transition model identified from test structure measurements has been adopted for the mixer design.

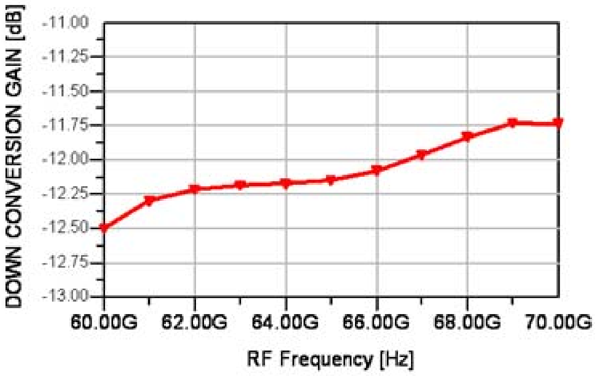

Fig. 5. The choice of small size diodes provides a good conversion loss of about 12dB across the bandwidth. The amplitude flatness is within 1dB across the bandwidth.

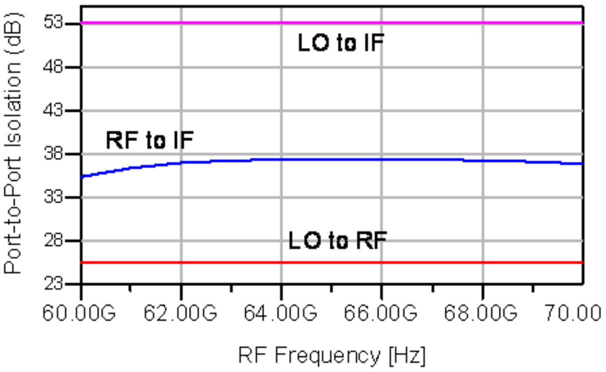

Fig. 6. Port to port isolation: the balanced structure presented by the Rat Race to the LO provides very high LO to IF suppression. LOtoRF and RFtoIF suppressions match the specifications as well.

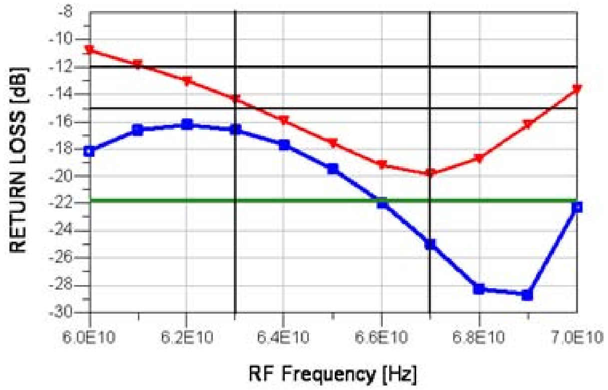

Fig. 7. Reflection coefficients at each port. The RF frequency is swept across the bandwidth 60-70GHz.

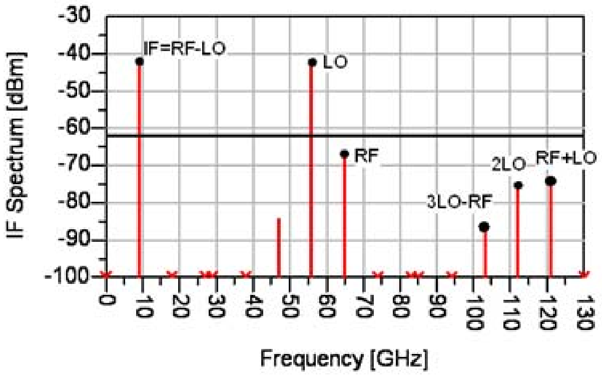

Fig. 8. IF output spectrum in the middle of the bandwidth. LO=56GHz, RF=65GHz and IF=9GHz. The horizontal line is 20dB below the IF level: LO harmonics and RF-LO spurious products are suppressed as requested in the specifications.

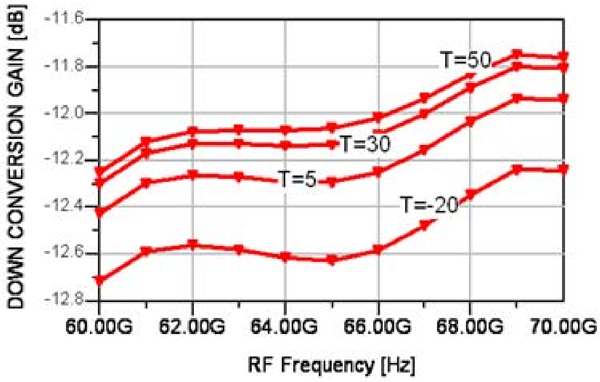

Fig. 9. Down conversion gain at different temperatures within the -20°C to 50°C requested range.

Figure 5 to figure 9 show the mixer simulated performances, which fulfil the design specifications. The inner bandwidth 63GHz-67GHz put in evidence in figure 7 is the operating bandwidth in which performances should be guaranteed.

V. CONCLUSIONS

A V band single balanced diode mixer has been designed for an on-board receiver. The system is a technology demonstrator for space applications at very high frequency. The mixer structure has been selected to match the specifications avoiding useless complexity (double balanced and/or biased structures) that can be very risky at such high frequencies. The simplicity of the structure made an accurate electromagnetic simulation of the circuit feasible; this is really mandatory at V band. The final circuit has got a small area (1873µm by 1053µm) and does not need power supply. The main challenges of the project are the use of a pHEMT diode technology at such high frequency and the need for a relative large bandwidth. Indeed, it has been quite complex to achieve gain flatness and the specified return losses over a 10GHz bandwidth (especially at the IF port), while keeping the structure as simple as possible to minimize the design risks at such high frequencies.

The project has been founded by Alenia Spazio that has developed the entire receiver module in the framework of an ESA contract. The scheduling of the taping-out of the foundry run lets us provide measurements at the conference.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance and support of Alenia Spazio.

REFERENCES

[1] A. Bessemoulin, C. Gaessler, P. Marschalf, P. Quentin, “A Chip-Scale Packaged Amplifier MMIC using Broadband Hot-Via Transitions”, Proceedings of the “33rd European .Microwave Conference”, Munich 2003.

[2] U. Di Marcantonio, l. Di Nardo, M. Tursini, M.C. Comparini et al. “Integrated Substrate Packaging Based on LTCC and HTCC Technologies for Highly Integrated Space Equipment”, Proceedings of the “11th GAAS Symposium”, Munich 2003.

[3] M. C. Comparini, J. R. Linkowski, P. Montanucci, E. Pizzuti, “Low-Cost, Low-Mass LTCC Down Converter For Communication Satellite Payloads”, Proceedings of the “11th GAAS Symposium”, Munich 2003.

[4] Yuh-Jing Hwang, Chun-Hsien Lien, HueiWang, et al. ”A 78–114 GHz Monolithic Subharmonically Pumped GaAs-Based HEMT Diode Mixer”, IEEE Microwave And Wireless Components Letters, Vol. 12, No. 6, June 2002.

[5] K.W. Chang, T.H. Chen, H. Wang and S. A. Maas, “Frequency Upconversion Behaviour of Singly Balanced Diode Mixers”, Antennas and Propagation Society International Symposium, 1991. AP-S. Digest , 24-28 June 1991.

[6] S. A. Maas, “Microwave Mixers”, Artech House, Norwood, MA, 1986.

[7] S. A. Maas, “Nonlinear Microwave Circuits”, Artech House, Norwood, MA, 1988.

[8] S.A. Maas, “The RF and Microwave Circuit Design Cookbook”, Artech House, Boston-London, 1998.

[9] Kwo Wei Chang, Huei Wang et al. “A W-Band Image-Rejection Downconverter”, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 12, December 1992.