<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *IEEE Microwave and Wireless Components Letters*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Dancila, D., Rottenberg, X., Tilmans, H A., De Raedt, W., Huynen, I. (2014)
Low Phase Noise Oscillator at 60 GHz Stabilized by a Substrate Integrated Cavity Resonator in LTCC.
IEEE Microwave and Wireless Components Letters, 24(12): 887-889
<http://dx.doi.org/10.1109/LMWC.2014.2361645>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-287412>

Low Phase Noise Oscillator at 60 GHz stabilized by a Substrate Integrated Cavity Resonator in LTCC

Dragos Dancila, Xavier Rottenberg, Harrie A. C. Tilmans, Walter De Raedt, and Isabelle Huynen

Abstract—In this letter we report a low phase noise oscillator exhibiting state-of-the-art phase noise characteristics at 60 GHz. The oscillator is stabilized by an off-chip substrate integrated waveguide (SIW) cavity resonator, manufactured in LTCC technology. The area on top of the cavity resonator is used to flip-chip mount the MMIC, realized in SiGe technology. Measured oscillators discussed in this paper operate at frequencies of 59.91 GHz, 59.97 GHz and 59.98 GHz. The measured phase noise at 1 MHz offset is -115.76 dBc/Hz, -115.92 dBc/Hz and -116.41 dBc/Hz, respectively. To our knowledge, the present hybrid oscillator has the lowest phase noise and highest figure of merit of integrated oscillators at V-band. The simulations are in very good agreement with the measured oscillation frequencies.

Index Terms—BiCMOS, phase noise, oscillator, LTCC, V-band

I. INTRODUCTION

THE actual trend in improving road safety consists in increasing the use of radar assistance systems as cruise control and collision warning, while advances are made towards proactive safety features such as collision mitigation and vulnerable road user detection. All these systems require the development of new radars at 24 GHz and 79 GHz bands, cheaper for introduction in a large panel of vehicles. Beside low-cost and mass fabrication, improving the performance of the signal generation requires low phase noise oscillators. Currently, a reference oscillator in an automotive radar, often consists in a dielectric resonator oscillator (DRO). This solution is rather large and requires additional manual fine trimming after packaging, as the dielectric resonator requires a very high position accuracy, especially at higher frequencies. Alternatively, cavity resonators were effectively used to stabilize Ka-band [1] and V-band [2], [3], [4] oscillators. To demonstrate the potential of using high Q-factor resonators, Mills et al. report on a WR15 waveguide tuner set-up used to load the negative resistance source of an un-diced SiGe MMIC. The performance reported is a phase noise of -123.11 dBc/Hz at 1 MHz offset of the carrier frequency of 59.36 GHz [5].

In this context, this paper presents an oscillator at 60 GHz in a hybrid multi-chip assembly configuration. This implementation is using the same MMIC as in [5], but here the MMIC is flip chip assembled on an LTCC substrate where a high Q

cavity resonator is integrated in the substrate. As a result, the state-of-the-art of low phase noise integrated oscillators, at V-band is improved. This oscillator could directly be used for very fast WLAN and the architecture could be adapted for automotive radar by adjusting the cavity resonator and MMIC.

II. OSCILLATOR CIRCUIT DESIGN

The MMIC chip ($1320 \times 1320 \mu\text{m}^2$) is realized by NXP Semiconductors in $0.25 \mu\text{m}$ QUBIC4X technology. The technology offers HBTs with $f_T/f_{MAX} = 130/140$ GHz and five metal layers back-end-of-line (BEOL), for high quality passive components and transmission lines [6]. The oscillator is designed as a series feedback, in a common base topology with a current mirror at the base of the oscillating transistor, see Fig. 1, as reported in [5] and [7]. The emitter periphery of the HBTs used in the circuit is $0.4 \times 10.3 \mu\text{m}^2$. The on-chip interconnect microstrip lines are fabricated in the BEOL layers and measured on-wafer. The RF power is conveyed from the collector to a common emitter buffer amplifier, see Fig. 1.

Fig. 1. Common base circuit schematic with LTCC SIW Cavity Resonator.

Two circuit versions are present on the MMIC die, different by a small variation of the microstrip length, at the transistor base. It results a slight variation of the phase presented at the emitter of the HBT connected to the cavity resonator. The MMIC chip photograph is shown in Fig. 2. The design of the oscillator is performed in ADS combining HFSS simulations of the flip-chip transition, off-chip microstrip interconnect and LTCC cavity resonator, foundry model for the HBT transistors and on-chip interconnections measurements.

D. Dancila is with Uppsala University, Angstrom Laboratory, Microwave Group, SE-751 21, Uppsala, Sweden. Formerly, with Universite catholique de Louvain, ICTEAM division. e-mail: Dragos.Dancila@angstrom.uu.se

X. Rottenberg, H.A.C. Tilmans and W. De Raedt are with IMEC, Kapeldreef 75, 3001 Leuven, Belgium

I. Huynen is with Universite catholique de Louvain, ICTEAM division, Place du Levant 3, 1348 Louvain-la-Neuve, Belgium

Manuscript received January 30, 2014; revised May 13, 2014.

Fig. 2. Photograph of MMIC chip realized by NXP Semiconductors.

III. LTCC CAVITY RESONATOR DESIGN

A rectangular cavity resonator is implemented as a substrate integrated waveguide (SIW) in LTCC. Layers of A6-M material of standard thickness 5–10 mil (127–254 μm) are stacked and sintered [8]. The shrinkage after sintering is 24%, therefore values of 96.5 μm for the dielectric below the microstrip line and 193 μm for the thickness of the cavity resonator are considered for the RF design. The relative permittivity of the substrate is $\epsilon_r = 5.7\text{--}6.1$ and the substrate loss is $\tan \delta = 0.002$. Gold top metallization of 10 μm thick is used. The resonance frequency f_{mnl} is given as follows [9]:

$$f_{mnl} = \frac{c_0}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (1)$$

with c_0 the speed of light, μ_r and ϵ_r the relative permeability and relative permittivity of the material filling the cavity. The modes of resonance available in the resonator are defined by the subscripts m, n and l . A square cavity resonator ($a = d$) is providing the highest unloaded Q-factor [9]. For the TE_{101} mode at 60 GHz the lateral dimensions, given tangential to the vias are $a = d = 1442 \mu\text{m}$. The thickness $b = 193 \mu\text{m}$ is imposed by the LTCC technology. The lateral dimensions are fine tuned using HFSS, considering a single row of vias (100 μm diameter and 200 μm pitch).

The coupling between the cavity resonator and the microstrip line (width, w) is realized by a circular aperture (diameter, o) opened in the ground metallization, see Fig. 3 and inset with cross section FF'. The fraction o/w fixes the value of the coupling coefficient, κ : higher o/w , higher κ . In addition, a lower line impedance lowers o/w for the same coupling coefficient. Consequently, three different configurations, described in Table I, were implemented. For different line impedances, a similar coupling coefficient is maintained. The feeding is analysed following the transfer of energy concept, introduced by Wheeler for the coupling between a waveguide and a cavity resonator [10]. The Q-factors are extracted from measurements with the software QZERO [11].

IV. RESULTS AND DISCUSSION

The simulations are in very good agreement with the measurements, with a simulated phase noise of -115 dBc/Hz at 1 MHz offset of the carrier frequency of 59.8 GHz. The low phase noise obtained is due to the high loaded Q-factor

Fig. 3. LTCC SIW cavity resonator based oscillators, at 60 GHz. Visible is the MMIC, incorporating two active circuits, flip-chip assembled. The cavity resonator is integrated into the LTCC substrate. Visible also are oscillators' output microstrip lines and DC biasing lines. Inset: cross section FF'.

TABLE I
MEASURED Q-FACTORS OF THE PROPOSED LTCC CAVITY RESONATORS

	Z_0 (Ω)	w (μm)	o/w	Q_0	Q_l	κ
A	30	325	1.6	166	24.5	5.75
B	25	415	1.2	165	26.9	5.11
C	30	325	1.5	197	25.7	6.65

of the LTCC cavity resonator. The measurements presented in Table II, show the frequency of oscillation, output power and phase noise. The oscillators are compared on the basis of the FoM defined in (2), following [3].

$$\text{FoM} = \mathcal{L}(f_m) - 20 \log \left(\frac{f_{osc}}{f_m} \right) + 10 \log \left(\frac{P_{DC}}{P_{OUT}} \right) \quad (2)$$

where f_{osc} is the oscillation frequency, f_m the offset frequency i.e. 1 MHz, P_{DC} the dissipated DC power, and P_{OUT} the RF output power. An external WR15 waveguide was used as resonator for the oscillator demonstrated in [5]. The state-of-the-art of monolithically integrated oscillators at V-band [14] was added for comparison.

The estimated output power is around +10 dBm. The estimated coaxial cable losses are 1.45 dB and 1.3 dB for the coaxial to waveguide adapter. The 150 μm pitch Ground-Signal-Ground probes are characterized by an insertion loss of 1 dB, at 60 GHz [12]. The RF probes (1.85 mm pPROBE 67 GHz GSG-150 μm pitch) were connected via 10 cm long RF coaxial cable (Totoku M-M 67 GHz) to a coaxial to waveguide adapter (Quinstar WR15) and to an Agilent V8486A V-Band power sensor, HP437B power meter. Therefore, 3.75 dB are added to the power meter read-out. The phase noise was measured using a signal analyser Agilent 5052B. A down conversion was performed using a WR15 mixer with the Agilent E8257D RF generator, as local oscillator (LO). The reference frequency was multiplied four times by a V-band active multiplier from Terabeam. The full measurement setup is presented in Fig. 4. The phase noise measurements are presented in Fig. 5, with details in Table II. The spectrum was measured using a signal analyser Agilent 5052B, centred

at the oscillator frequency with a span of 13 MHz and 1001 points, see Fig. 6. The raw measurements are post-processed considering the Intermediate Frequency, IF = 240 MHz and the local oscillator frequency, $f_{LO} = 14.932$ GHz for the biasing point ($V_{cc} = 2$ V, $V_{be} = 1$ V). Around this point, the variation of the oscillator frequency with V_{cc} is about 70 MHz/V.

Fig. 4. Measurements set-up: a) block diagram b) close-up on the WR15 mixer from Ducommun and active multiplier from Terabeam.

Fig. 5. Measured Phase Noise of the proposed oscillators. The phase noise at 1 MHz offset from the carrier frequency is consistently around -116 dBc/Hz.

Fig. 6. Measured Spectrum of the proposed oscillators. The output power is consistently around 10 dBm.

V. CONCLUSION

A series-feedback hybrid multi-chip integrated oscillator using SIW cavity resonator in LTCC and a SiGe MMIC has been successfully manufactured and is operating with state-of-the-art performance at V-band. For the best case, a phase noise of -116.41 dBc/Hz is measured at 1 MHz offset of the oscillation frequency of 59.97 GHz. The measured

TABLE II
STATE OF THE ART OF INTEGRATED OSCILLATORS AT V-BAND

Ref.	f_{osc} (GHz)	Phase Noise @ 1MHz (dBc/Hz)	P_{OUT} (dBm)	P_{DC} (mW)	FoM (dBc/Hz)	Technology IC/cavity
[2]	59.88	-112	9.7	102	-197	GaAs/Si-KOH
[3]	55.77	-106	-3.7	76.4	-178	CMOS/Si-KOH
[4]	54	-102	5.5	90	-183	SiGe/MCM-D
[13]	57.5	-112	-14	-	-	SiGe/DR
[5]	59.36	-123.11	3.42	78.5	-203	SiGe/WR15
[14]	61.59	-108	-2	145	-180	SiGe/-
A	59.91	-115.76	9.48	198	-197	SiGe/LTCC
B	59.98	-115.92	9.87	160	-199	SiGe/LTCC
C	59.97	-116.41	10.59	133	-201	SiGe/LTCC

output power is 10.59 dBm, with a corresponding DC-to-RF efficiency of about 8.61% and the FoM is -201 dBc/Hz.

ACKNOWLEDGEMENT

This work was realized within the framework of the European research project 3D μ Tune (IST-2005-027768). The authors would like to thank Andreas John from AC Microwave GmbH, now with Hella KGaA Hueck & Co. and John Mills from Philips Research for the MMIC design and manufacture, respectively. The authors are grateful to the Research Science Foundation (FRS-FNRS), Belgium. Dragos Dancila was supported by a F.R.I.A. Ph.D. fellowship.

REFERENCES

- [1] Y. Kwon *et al.*, "A Ka-band MMIC oscillator stabilized with a micro-machined cavity," *IEEE Microw. Guid. Wave Lett.*, vol. 9, pp. 360-362, Sep. 1999.
- [2] S. Song *et al.*, "A V-Band Parallel-Feedback Oscillator With a Micro-machined Cavity Integrated on a Thin-Film Substrate," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, pp. 107-109, Feb. 2009.
- [3] Y. Koh *et al.*, "A V-band low-phase-noise CMOS oscillator using a micro-machined cavity," *IEEE MTT-S International Microw. Symp. Digest*, 2009, pp. 689-692. doi: 10.1109/MWSYM.2009.5165790
- [4] D. Dancila *et al.*, "V-band low phase noise oscillator based on a cavity resonator integrated in the silicon substrate of the MCM-D platform," *Microw. Opt. Technol. Lett.*, vol. 54, no.8, pp.1788-1792. doi: 10.1002/mop.26946
- [5] J. B. Mills *et al.*, "Waveguide tuner stabilized ultra low phase noise 60 GHz SiGe:C oscillator MMIC," *IEEE 11th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems (SiRF)*, 2011, pp.77-80. doi: 10.1109/SiRF.2011.5719326
- [6] P. Deixler *et al.*, "QUBiC4X: an ft/fmax = 130/140GHz SiGe:C-BiCMOS manufacturing technology with elite passives for emerging microwave applications," *In Proc. Meeting Bipolar/BiCMOS Circuits and Technology*, 2004, pp. 233-236. doi: 10.1109/BIPOL.2004.1365788
- [7] I. Ocket *et al.*, "60 GHz ultra low phase noise SiGe common base oscillator using a wirebond coupled MCM integrated micromachined cavity resonator," *IEEE Bipolar/BiCMOS Circuits and Technology Meeting*, 2008, pp.182-185. doi: 10.1109/BIPOL.2008.4662739
- [8] Ferro Electronic Material. (2013, Feb.). *A6-M High Frequency, High Reliability LTCC Tape System* [Online]. Available: <http://www.ferro.com>
- [9] D. M. Pozar, *Microwave Engineering*. Wiley, 2005.
- [10] H. A. Wheeler, "Evaluation of a Coupling Hole Between Two Resonant Cavities," *PTGMIT National Symposium Digest*, 1963, pp. 63-68.
- [11] D. Kajfez, *Q Factor*. Vector Fields, 1994.
- [12] GGB Industries Inc. *Picoprobes - Model 67A* [Online]. Available: <http://www.ggb.com/67a.html>
- [13] F. X. Sinnesbichler *et al.*, "A Si/SiGe HBT dielectric resonator push-push oscillator at 58 GHz," *IEEE Microw. and Guid. Wave Lett.*, vol.10, pp.145-147, Apr. 2000. doi: 10.1109/75.846927
- [14] A. Chakraborty *et al.*, "A low-phase-noise monolithically integrated 60 GHz push-push VCO for 122 GHz applications in a SiGe bipolar technology," *Bipolar/BiCMOS Circuits and Technology Meeting*, 2013, pp.195-198.