

High-Q Ku-band Microstrip Spiral Resonator in Fan-out Wafer-Level Packaging (FoWLP) Technology for VCO Applications

Mykola Chernobryvko
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
mykola.chemobryvko@izm.fraunhofer.de

Michael P. Kaiser
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
michael.kaiser@izm.fraunhofer.de

Kavin Senthil Murugesan
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
kavin.senthil.murugesan@izm.fraunhofer.de

Dan Kuylenstierna
Chalmers University of Technology,
Gothenburg, Sweden
dan.kuylenstierna@chalmers.se

Julia-Marie Köszegei
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
julia-marie.koeszegei@izm.fraunhofer.de

Robert Gernhardt,
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
robert.gernhardt@izm.fraunhofer.de

Tanja Braun
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
tanja.braun@izm.fraunhofer.de

Ivan Ndip
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
ivan.ndip@izm.fraunhofer.de

Martin Schneider-Ramelow
Fraunhofer Institute for Reliability and
Microintegration
Berlin, Germany
martin.schneider-ramelow@izm.fraunhofer.de

Abstract— In this paper, a planar spiral resonator operating at 13 GHz is investigated. The resonator was fabricated using fan-out wafer level packaging (FoWLP) technology. The field analysis highlights the importance of via fence. Two thick film resistors suppress an undesired resonance in proximity of targeted one. The measurements demonstrate a very good correlation in comparison with full-wave simulations. The measured Q-factor defined based on analysis of feedback oscillatory system is about 48. The proposed configuration is suitable for voltage-controlled oscillators (VCOs) with a resonator realized in package.

Keywords—resonator, Q-factor, Ku-band, fan-out wafer level packaging, VCO

I. INTRODUCTION

Modern trends in miniaturisation and demands for higher resolution have prompted radar technologies to explore and utilise W-band frequencies, i.e. 75-110 GHz, to exploit the higher available bandwidth [1], [2]. Moreover, due to low atmospheric losses W-band frequencies provide better Signal-to-Noise ratio (SNR) than the previously used frequency bands at around 24 GHz and 60 GHz. Consequently, current research activities are concentrated on the development of components for novel radar systems operating at the W-band [3].

A crucial part of radar systems is the frequency synthesis with low phase noise, e.g. by applying Phase-Locked-Loops (PLLs), where voltage-controlled oscillators (VCOs) are required in order to relate the phase of the output signal to a reference input signal [4]. Therefore, improving the phase noise performance of the VCO is beneficial for the purity of the frequency synthesiser's output signal. A VCO can be implemented on chip-level in combination with a package-integrated resonator. Due to the advantageous packaging material properties, a high Q-factor can be achieved providing better phase noise performance in contrast to resonators realized on-chip. To overcome insufficient gain of active devices at high frequencies, the frequency synthesis can occur at lower frequencies and the output signal is then transferred

to the actual carrier through frequency multipliers. As shown in [5] a 77 GHz carrier can be generated at Ku-band, i.e. at about 13 GHz, followed by a x6 frequency multiplication. Thus, the requirements on the VCO design become more cost-efficient and flexible as well as its external resonator is more robust towards fabrication tolerances providing wider tuning ranges.

Various resonator configurations being suitable for package integration were investigated in literature. Substrate integrated waveguide (SIW) resonator [6] has the potential to be a good candidate due to its excellent power handling characteristics. However, such resonator requires manufacturing of via rows with high precision in the alignment. Oscillators based on dielectric resonator (DROs) are known as preferable for signal synthesis [7]. Though, such configurations are complex and expensive due to challenges in realization of low-loss dielectrics with high dielectric permittivity. Alternatively, the planar spiral microstrip resonator described in [8] is simple in realisation. Nevertheless, a thorough analysis of this configuration is essential in which Q-factor is defined based on the phase slope of the transfer function. This is necessary for developing of VCO with low phase noise performance.

In order to realise a VCO with an off-chip resonator a suitable packaging technology has to be chosen. Recently, Fan-out Wafer-Level Packaging (FoWLP) has emerged as a key technology for the integration of passive high frequency components [9], [10] offering a great opportunity for planar resonator realisation. Such structures can benefit from the advantageous shorter RF connection path to IC avoiding wire bonds or bumps, what is crucial in passive structures integration. Some research activities have already demonstrated the importance of passive components integration into a FoWLP showing an improved Q-factor [11], [12].

In this contribution, a FoWLP-based resonator is investigated operating at 13 GHz. The feeding microstrip line (MSL) and electro-magnetically coupled to it spiral form a

planar resonator in the redistribution layer (RDL). The resonator's reference layer is located on a metallised epoxy molding compound (EMC) on top of the RDL. To suppress an undesired resonance of the planar resonator, two thick film resistors were embedded into the EMC. The measurements of the fabricated sample are in good correlation with modelling showing high Q-factor.

The paper, first, presents the definition of Q-factor and the FoWLP-based planar spiral resonator configuration with detailed explanations of the stack-up in Section II. Moreover, the importance of field analysis is discussed. In Section III, results of the full-wave simulation and the measurement of the fabricated structure are highlighted. Section IV finalises the paper with conclusions of the investigation.

II. RESONATOR CONFIGURATION AND MODELING

A. Definition of Q-Factor

The investigated Ku-band resonator is developed to serve as an off-chip LC tank for a VCO. Therefore, a proper definition of the term Q-factor is essential. The package-integrated single port spiral resonator can be considered as a feedback system. For the feedback oscillatory system, the open loop Q-factor is defined based on the phase of the transfer function

$$Q = (\omega_0/2)(d\phi(H)/d\omega), \quad (1)$$

with ω_0 defining the resonance frequency of LC tank and $d\phi(H)/d\omega$ is the phase slope of the resonator transfer function [13], [14]. Taking into account that the designed resonator is a single port structure, Z_{11} of impedance parameters is used as a transfer function, which leads to the final definition of the Q-factor to be

$$Q = (\omega_0/2)(d\phi(Z_{11}(\omega))/d\omega). \quad (2)$$

It is worth to mention that the reflection S_{11} of S-parameters cannot serve as a transfer function due to the dependency on the port impedance.

B. Stack-Up and Materials

The proposed planar microstrip spiral resonator was developed for the integration in the RDL of a FoWLP-based platform [15]. A stack-up of the applied package configuration is illustrated in Fig. 1. The RDL consists of three polyimide (PI) layers and two copper layers. The thickness of each PI layer is 8 μm . The copper layers are denoted as Cu Layer 2 and Cu Layer 3 are 3 μm and 5 μm , respectively. On top of the RDL, an EMC of 300 μm

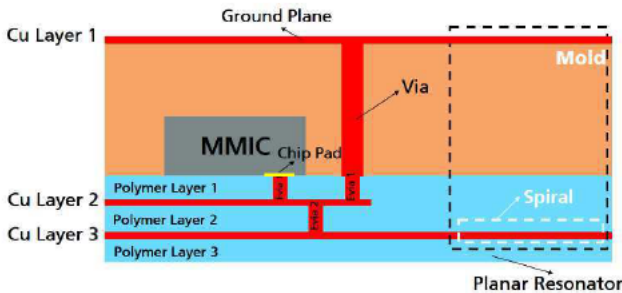


Fig. 1: Stack-up for a planar spiral resonator in FoWLP technology.

thickness is applied being metallised with another Cu layer of 3 μm thickness (Cu Layer 1). The PI material was characterized using the procedure described in [16] with corresponding dielectric permittivity $\epsilon_{r,PI} = 3.5$ and dielectric loss $\tan\delta_{PI} = 0.008$ at 12 GHz. Similarly, the EMC properties were extracted at 12 GHz yielding the permittivity $\epsilon_{r,EMC} = 3.66$ and the dielectric loss $\tan\delta_{EMC} = 0.004$.

The Cu Layer 1 acts as the reference for the resonator in the RDL. The MSL and the electromagnetically coupled spiral were realized on Cu Layer 3. For the vertical interconnections between Cu Layer 3 and Cu Layer 2 standard single via transitions were implemented, whereas the interconnections between Cu Layer 2 and Cu Layer 1 are challenging, since via rows through the PI Layer 1 must be properly aligned with the through mold via (TMV). In this case, the TMVs have not been realised by drilling and metallizing the openings, but have thus been manufactured separately as pick-and-place components. Further details of this procedure are described in [17].

C. Modelling and Simulations

The design of a planar microstrip spiral resonator is shown in Fig. 2. Fig. 2 (a) illustrates a top view of the simulation model. As can be seen, the feeding of the resonator starts with a coplanar waveguide (CPW) section to ensure a proper connection to the pads of an integrated circuit (IC), which are typically in Ground-Signal-Ground (GSG) configuration. Another reason for the CPW feeding is the need to measure the planar resonator in stand-alone test structures without any VCO in a wafer probing station. The measurements were performed using RF probes whose tips are also available in GSG configuration. The CPW is followed by an MSL section. Both transmission line sections designed to be 50 Ω were matched using tapering. The resonator itself consists of a non-uniform, spirally bent transmission line electro-magnetically coupled to the MSL. The gap between MSL and resonator is 20 μm . The resonator produces series and parallel resonances in proximity to each other. One of them should be damped to ensure that a VCO employing such resonator generates oscillations without spurious components. In order to suppress spurious resonance, two 80 Ω surface mount device (SMD) resistors are placed in parallel at the end of the MSL and tied to ground. The side view of the modelled configuration including one of the SMD resistors is shown in Fig. 2 (b).

The electromagnetic simulations were carried out with Ansys HFSS, a 3D Finite Element Method (FEM) full wave solver. The modelling includes also optimisation of the resonator. Particularly, the position of the spiral along the MSL feeding line and spiral shape were tuned to the best Q-factor. Moreover, the field analysis is essential for such a configuration, since the resonator is not shielded. Therefore, the design should ensure that the structure operates without significant leakage, which potentially influences the operation of IC or further system components. In Fig. 2 (c), the magnetic field at the resonance frequency of 12.6 GHz is visualised showing a high magnitude at the spiral cross section, indicating a proper functioning of the modelled resonator. Additionally, the H-field is shown in the plane crossing the protective via fence to analyse its effectiveness. As can be seen, the field is only strong at the region of the CPW feeding line demonstrating that the via fence blocks properly undesired penetration of electromagnetic fields. The via fence

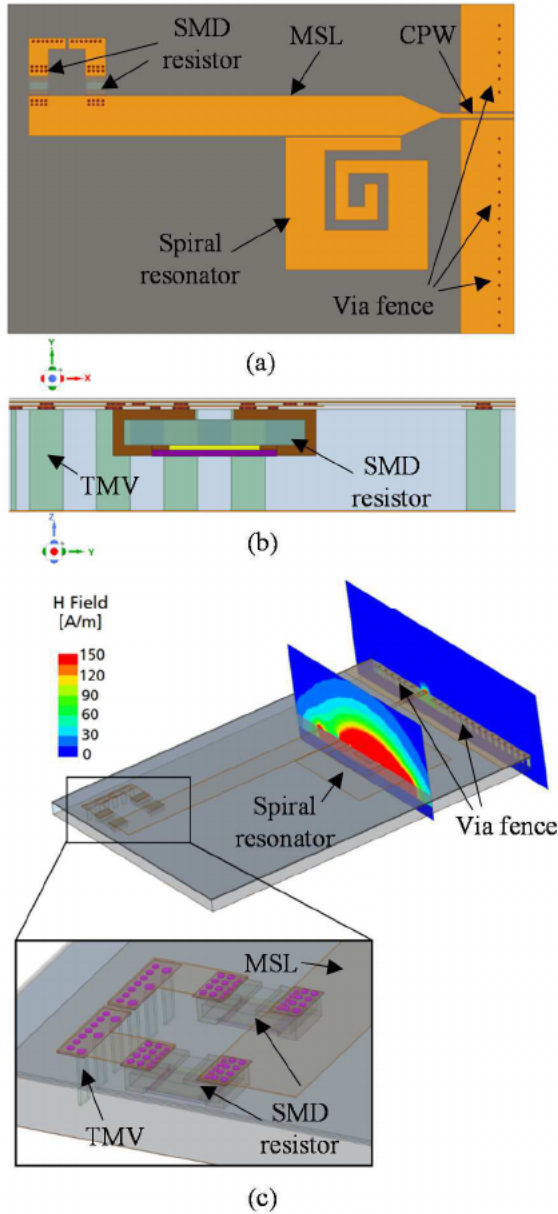


Fig. 2. Ku-band planar spiral resonator configuration operating at 12.6 GHz. (a) Top view. (b) Cross sectional view including SMD resistor. (c) Isometric view with cross sections representing H field and details for embedded SMD resistors.

was introduced on design stage in the region where leakage of fields at resonance frequency was noticed.

III. RESULTS OF SIMULATION AND MEASUREMENT

Fig. 3 shows a top view on the fabricated planar spiral resonator including the embedded SMD resistors. A comparison between the design and the actual manufactured geometrical values are provided in TABLE I. In general, the fabricated structure shows a good correlation to the design values with a maximum deviation of approximately 4%. However, the spacing between the MSL and the spiral (gap) being the smallest value in TABLE I is doubled due to over-etching.

The RF measurements were performed using the Keysight Vector Network Analyser (VNA) E8361A, a wafer prober system and a 250 μm pitch GSG probe. The measurements were carried out from 10 GHz to 15 GHz at

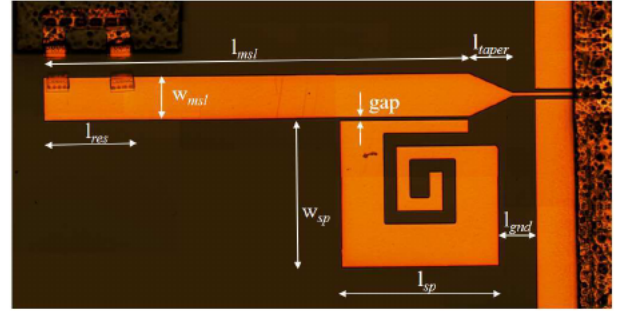


Fig. 3. Top view on fabricated Ku-band planar spiral resonator in FoWLP technology.

room temperature. The VNA was calibrated with the short-open-load-through (SOLT) method by means of a standard calibration substrate. This ensures the reference impedance of 50 Ω and the reference planes to be near the tip of the probe.

The VNA measures S-parameters that can be converted to Z-parameters to apply (2) for Q-factor extraction. The simulated and measured curves are shown in Fig. 4. Note that the model was re-simulated using the actual measured values from the fabricated sample. Fig. 4 (a) displays the reflection S-parameters. A resonance at 12.9 GHz can be identified in the simulated results, whereas the measured structure reaches its resonant behaviour at approximately 13.1 GHz, hence, a shift of about 200 MHz can be identified. The measured return losses are below -10 dB in the frequency ranges 10.6-11.9 GHz and 13.6-13.8 GHz while simulated return losses are lower than -10 dB in the bands of 10-12 GHz and 13.2-15 GHz. Lower values of return losses outside the resonance frequency result in better purity of oscillations generated by VCO. Furthermore, the small offset can be seen even more clearly in Fig. 4 (b), where the comparison between simulated and measured Q-factor of the planar spiral resonator is shown. The spurious resonance at approximately 13.55 GHz could not be suppressed perfectly. Nevertheless, a measured Q-factor of 48 is achieved in this configuration, which is approximately two times higher than on-chip resonators demonstrate [18].

The deviation between simulation and measurement is associated with the modelling of the SMD resistors. During the design phase, they were assumed to be ideal components. However, real resistors include some parasitics, e.g. due to

TABLE I. COMPARISON OF MEASURED GEOMETRICAL PARAMETERS WITH RESPECT TO NOMINAL DESIGN OF THE SPIRAL RESONATOR

	Design value, (mm)	Measured value, (mm)	Var. w.r.t. design value (%)
l_{msl}	5.6	5.58	-3.5
w_{msl}	0.6	0.585	- 2.5
l_{taper}	0.6	0.59	-1.7
l_{res}	1.15	1.165	1.3
gap	0.02	0.04	100
l_{sp}	2.14	2.12	-0.9
w_{sp}	2	1.98	-1
l_{gnd}	0.49	0.51	-4.1

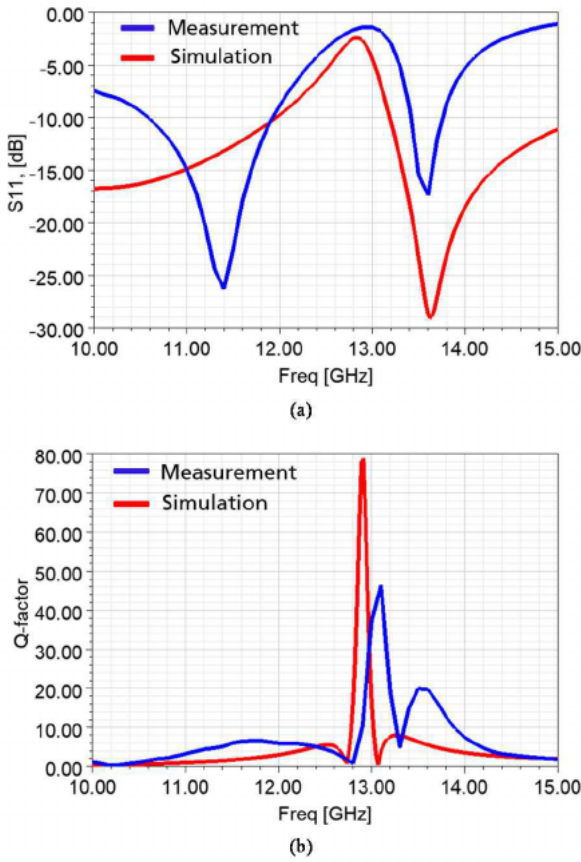


Fig. 4. Comparison of simulated and measured results for the planar spiral resonator in FoWLP. (a) Reflection S-parameters. (b) Q-factor.

their packaging, which can be modelled as series inductance and parallel capacitance to the resistor. Therefore, the SMD resistors must also be thoroughly investigated to model more accurate the planar resonator. In addition, since Q-factor is dependent on how fast the phase of Z_{11} is changing (5), any inaccuracy in modelling might significantly influence the phase slope close to a resonant frequency. Consequently, measured Q-factor values are different from the simulation results.

IV. CONCLUSION

In the present work, a planar spiral resonator was successfully designed, fabricated and characterised in FoWLP. The measurements show a good correlation to the full-wave simulations. A measured Q-factor of 48 shows a significant improvement compared to on-chip solutions. This reveals a great potential of FoWLP for the implementation of VCOs with package-integrated resonators. Starting point for future investigations is an improved modelling of the SMD resistors, which considers their parasitic properties or even approaches making the discrete components obsolete. In addition, a sensitivity analysis should be performed for the expected process and manufacturing tolerances to determine limits within which the planar spiral resonator demonstrates stable performance.

ACKNOWLEDGMENT

This work was financed by the CleanSky 2 program within the European Union's Horizon 2020 research and innovation

framework, grant agreement no. 821270 "GaN mm-wave Radar Components Embedded - GRACE".

REFERENCES

- [1] D. A. Murrell, S. A. Lane, N. P. Tarasenko and C. Christodoulou, "A review of spaced based RF propagation experiments and examination of a new interest in W/V band (40–110 GHz) studies," in 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), 2016.
- [2] I. Kallfass, et. al., "Towards the Exploratory In-Orbit Verification of an E/W-Band Satellite Communication Link," in 2021 IEEE MTT-S International Wireless Symposium (IWS), 2021.
- [3] T. N. Thi Do, Y. Yan and D. Kuylenstierna, "A low phase noise W-band MMIC GaN HEMT oscillator," in 2020 IEEE Asia-Pacific Microwave Conference (APMC), 2020.
- [4] C. Zech, et. al., "A compact W-band LFMW radar module with high accuracy and integrated signal processing," in 2015 European Microwave Conference (EuMC), 2015.
- [5] J.-H. Song, C. Cui, S.-K. Kim, B.-S. Kim and S. Nam, "A Low-Phase-Noise 77-GHz FMCW Radar Transmitter With a 12.8-GHz PLL and a x6 Frequency Multiplier," IEEE Microwave and Wireless Components Letters, vol. 26, no. 7, p. 540–542, 2016.
- [6] Z. Chen, W. Hong, J. Chen and J. Zhou, "Design of High-Q Tunable SIW Resonator and Its Application to Low Phase Noise VCO," IEEE Microwave and Wireless Components Letters, vol. 23, no. 1, p. 43–45, 2013.
- [7] S. Huang, Z. Shi, X. Zhang, X. Yu and P. Chen, "DRO Design for Millimeter Wave Terminal Communication System," in 2022 International Conference on Microwave and Millimeter Wave Technology (ICMMT), 2022.
- [8] M. S. Abouyoussef, A. M. El-Tager and H. El-Ghitani, "Quad spiral microstrip resonator with high quality factor," in 2018 35th National Radio Science Conference (NRSC), 2018.
- [9] T. Braun, K.-F. Becker, M. Wohrmann, M. Topper, L. Bottcher, R. Aschenbrenner and K.-D. Lang, "Trends in Fan-out wafer and panel level packaging," in 2017 International Conference on Electronics Packaging (ICEP), 2017.
- [10] T. Braun, et. al., "Fan-out wafer level packaging for 5G and mm-Wave applications," in 2018 International Conference on Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC), 2018.
- [11] K. S. Murugesan, et. al., "High Quality Integrated Inductor in Fan-out Wafer-Level Packaging Technology for mm-Wave Applications," in 2020 50th European Microwave Conference (EuMC), 2021.
- [12] M. Wojnowski, V. Issakov, G. Knoblinger, K. Pressel, G. Sommer and R. Weigel, "High-Q embedded inductors in fan-out eWLB for 6 GHz CMOS VCO," in 2011 IEEE 61st Electronic Components and Technology Conference (ECTC), 2011.
- [13] T. Ohira, "What in the World Is Q? [Distinguished Microwave Lecture]," IEEE Microwave Magazine, vol. 17, no. 6, p. 42–49, 2016.
- [14] B. Razavi, "A study of phase noise in CMOS oscillators," IEEE Journal of Solid-State Circuits, vol. 31, no. 3, p. 331–343, 1996.
- [15] R. Gernhardt, et. al., "An Overview About the Excimer Laser Ablation of Different Polymers and Their Application for Wafer and Panel Level Packaging," in 2019 International Wafer Level Packaging Conference (IWLPC), 2019.
- [16] A. Kanitkar, et. al., "Fork-Coupled Resonators for Characterization of Mold Material for 5G Applications," in 2020 23rd International Microwave and Radar Conference (MIKON), 2020.
- [17] T. Braun, et. al., "3D stacking approaches for mold embedded packages," in 18th European Microelectronics & Packaging Conference (EMPC), 2021.
- [18] I. Mansour et. al., "70 % Improvement in Q-Factor of Spiral Inductor and its Application in Switched K-Band VCO Using 0.18 μm CMOS Technology" in 2018 Asia-Pacific Microwave Conference (APMC), 2018.