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A COMPARISON OF BASIC 94 GHZ PLANAR TRANSMISSION LINE RESONATORS IN COMMERCIAL BICMOS BACK-END-OF-LINE PROCESSES

Abstract — A comparative simulation study of planar 94 GHz resonators in a typical BiCMOS BEOL stack-up is presented, with the effect of chip passivation included. It is shown that Q-factors of between 3 and 15 can be obtained, depending on transmission medium and ground plane layer choice. Straight half-wavelength and shorted quarter-wavelength microstrip resonators are shown to outperform CPW, GCPW and hairpin resonators, with highest Q-factors obtained where the lowest available metallization layer is used as ground plane. Q-factors of above 10 may also be achieve in the absence of any ground plane in CPW, which may be implemented in processes (such as GaAs or GaN) where multiple metallization layers are not readily available.

Introduction

Millimeter-wave receivers (30 – 110 GHz) have found widespread terrestrial commercial application in passive imaging [1] and automotive RADAR [2] due to the compact size and sharp resolution over short distances. Due to congestion in traditional GSM and LTE frequencies, attention is being turned to the under-utilized mm-wave spectrum for short- and medium-range communications applications [3].

Monolithic integration of these future systems [4] presents significant cost and size advantages as opposed to waveguide implementations [5], with Silicon-Germanium Bipolar Complementary Metal-Oxide-Semiconductor (SiGe BiCMOS) providing full mixed-signal mm-wave system-on-chip integration possibilities [6]. To enable complex signal routing for system-on-chip applications, the back-end-of-line (BEOL) of RFCMOS and BiCMOS feature multiple metallization layers [6] which may be used to implement complex 2.5D distributed elements.

A significant drawback to complete on-chip systems is the high losses associated with passive circuitry surrounding the active transistors on the semiconductor wafer [7]. This is especially problematic in the implementation of on-chip filters, since the mid-band filter insertion loss is inversely proportional to the achievable resonator Q-factor [8]. Typical achieved unloaded quality factors (Q-factors) for on-chip resonators at V- and W-band frequencies have been demonstrated only up to 83 [9] for compound transmission line resonators, 43 for shielded transmission line resonators [10], 25 for single transmission line resonators [11] and below 15 for LC tanks [11].

This paper presents comparative simulation results on different common planar transmission line resonator topologies in an effort to identify suitable candidates for future W-band on-chip filter implementations in an RF CMOS or SiGe BiCMOS back-end process. This includes variations in resonator geometry, transmission line geometry and grounding metallization. All geometries are evaluated at 94 GHz where a local minimum in atmospheric attenuation [12] exists suitable for medium range communications.

Simulation Parameters

Simulations were performed in the 3D FEM solver provided by ANSYS HFSS. Open radiating boundaries were chosen at all but the lower XY-plane, which was chosen as PEC boundary to replicate the wafer probe platen.

The BEOL stack-up used throughout this paper is that of the IHP SG25 process (Figure 1), as is it is offered as a stand-alone BEOL prototyping service by IHP. It is expected that these results are indicative of achievable performance in most W-band capable SiGe BiCMOS processes such as the IBM 8HP or STMicroelectronics 9MW processes. The only requirements are that multiple back-end metallization layers are available, preferably with two thick (> 2 μm) top metal layers.

All resonators are excited symmetrically by two ports, and the unloaded Q-factor Q_0 extracted from the scattering parameters [13] as

$$Q_0 = \frac{Q_L}{1 - \left|S_{21}\right|_{f=f_0}} \quad (1)$$

where f_0 is the resonant frequency and $|S_{21}|$ is the transmission magnitude at resonance. Q_L is the loaded Q-factor calculated from the transmission parameters as

$$Q_L = \frac{f_0}{\Delta} \quad (2)$$

with Δ defined as the -3 dBc transmission bandwidth shown in Figure 2.

Excitation of millimeter-wave passive structures on-chip in simulation is performed via lumped port approximating the Ground-Signal-Ground (GSG) wafer probe, as proposed in [14] and pictured in Figure 3. The passivation and upper oxide depositions are windowed out to allow for probing, as is done in manufacturing and testing. A key simulation parameter is that the passivation is preserved over the resonator geometry, in an effort to accurately characterize the passivation's contribution to Q-factor reduction.

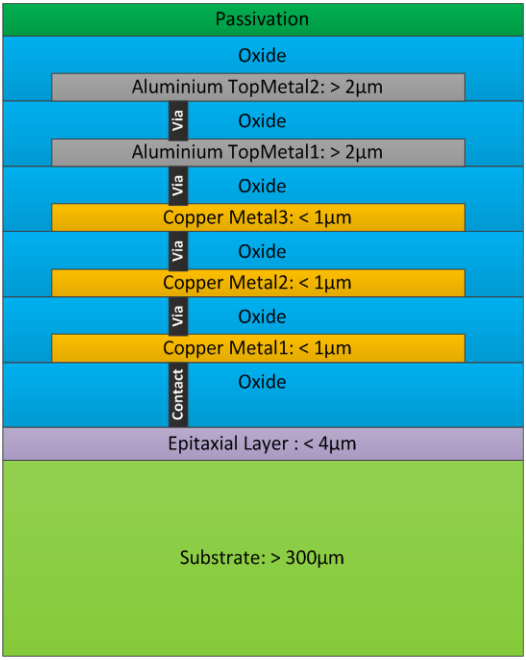

Fig. 1. Typical SiGe BiCMOS BEOL stack-up

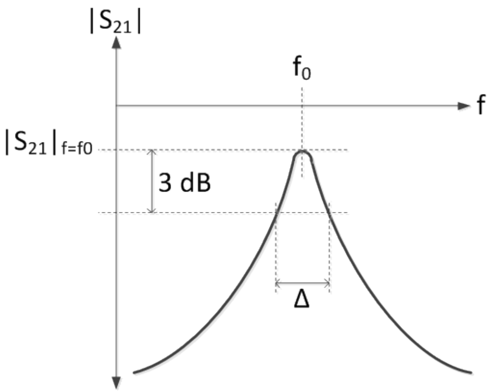

Fig. 2. Calculation parameters for Q_0 from $|S_{21}|$ response

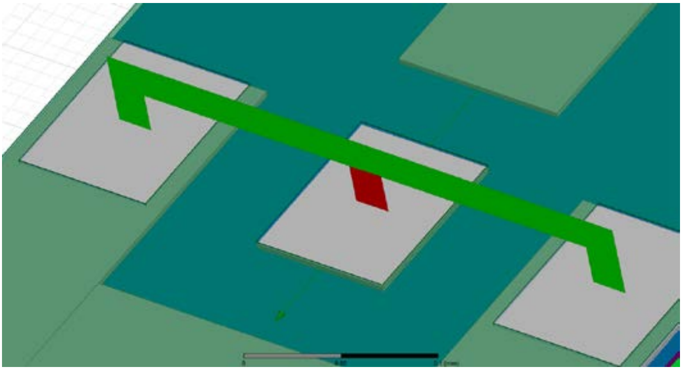

Fig. 3. Simulated GSG probe of on-chip CPW line

Half-wavelength straight lines

The half-wavelength planar transmission line resonator is one of most commonly used resonators in the synthesis of coupled resonator filters [8]. In a multi-layer planar media (such as an RFCMOS or BICMOS BEOL) implementation as microstrip and coplanar waveguide (both conductor backed grounded coplanar waveguide (GCPW) and ungrounded CPW) are viable for realizing 94 GHz resonators without requiring interconnect vias to re-route the RF signal to lower metallization layers (as is required for stripline). Half-wave resonators were dimensioned as shown in Figure 4 and simulated. Resonator length *l* was adjusted to achieve resonance at 94 GHz, whilst width *w* and coplanar waveguide gap width *g* (where applicable) adjusted to achieve optimal Q-factor. The results are shown in Table 1.

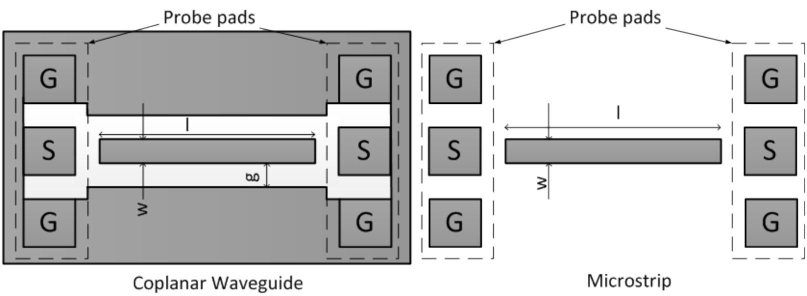

Fig. 4. Layout of half-wavelength straight resonator test geometries.

Table 1. Unloaded Q-factors for straight half-wavelength resonators

Geometry	**Signal layer**	**Ground layer**	**Length (µm)**	**Width (µm)**	**Gap width (µm)**	Q_0
Microstrip	TM2	TM1	680	105	-	5.40
Microstrip	TM2	M1	770	60	-	12.86
CPW	TM2	-	690	60	35	4.25
GCPW	TM2	TM1	705	20	25	3.47
GCPW	TM2	M1	ready	23	25	5.45

From the results it is apparent that wider resonator widths provided higher Q-factors in microstrip with narrower widths and gaps providing better performace in CPW or GCPW. Greater separation between the signal line and ground plane also improved Q-factor. Both results are in line with what is observed in half-wavelength resonators in soft substrates. Microstrip resonators outperform CPW and GCPW resonators in all cases.

Hairpin resonators

A common variation to the straight half-wavelength line is to bend the line into the shape of a hairpin [15] as shown in Figure 5. Hairpin resonators typically have higher Q-factors than straight half-wavelength lines, but are limited in how they are shaped by the aspect ratio (*w:l*) of the line.

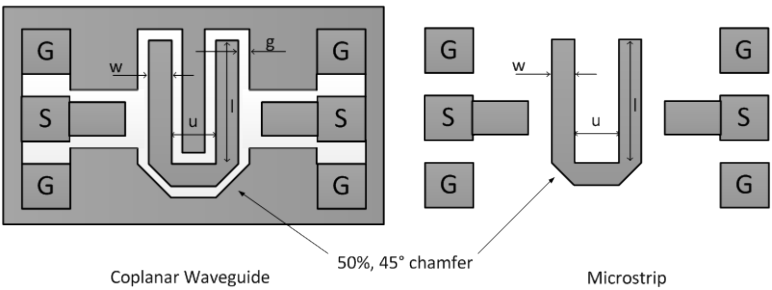

Fig. 5. Layout of hairpin resonator geometries

Table 2. Unloaded Q-factors for hairpin half-wavelength resonators

Geometry	**Signal layer**	**Ground layer**	**Length (µm)**	**Width (µm)**	**Spacing (µm)**	**Gap width (µm)**	Q_0
Microstrip	TM2	TM1	310	35	35	-	3.52
Microstrip	TM2	M1	360	11	20	-	5.10

CPW	TM2	-	290	30	60	35	7.54
GCPW	TM2	TM1	315	10	30	20	3.45
GCPW	TM2	M1	348	10	30	15	5.38

With the exception of the CPW resonator, no improvement in resonator Q-factor is observed by bending the line into the shape of a hairpin. The observed microstrip hairpin resonator Q-factor of around 5 is a 75% reduction on the previously reported result of Q_0 = 20 at 70 GHz [11], although the use of the lowest possible metal layer for ground is again shown to be best practice. The hairpin alteration to the straight line is best implemented by making the hairpin width *u* as narrow as possible (as is found in soft substrate implementations too) toe the point where the ground plane septum between the hairpin legs is omitted altogether. The exception is the CPW hairpin, where greater separation between hairpin legs provided greater Q-factors.

The improved CPW resonator Q-factor obtained by removing the lower ground plane of the GCPW line indicates that 94 GHz resonators may be feasible in processes where multiple metallization layers are not readily available, such as GaAs or GaN [6].

Quarter-wavelength shorted lines

Quarter-wavelength resonators are often used moderate- and wide-band interdigital or combline filters [8]. By their very definition they are more compact than half-wavelength resonators, which is advantageous for system-on-chip devices where die area comes at a premium. One drawback to the implementation of short-circuited lines on-chip is the fairly high resistivity of the on-chip tungsten vias required to ground a microstrip line [16]. This shortcoming may be overcome either by placing multiple parallel vias in a dense array to create an effective low-resistance connection to ground (with catch pads on every intermediate metal layer), or by implementing short-circuited lines in CPW and GCPW and thereby removing the need for high resistance vias altogether.

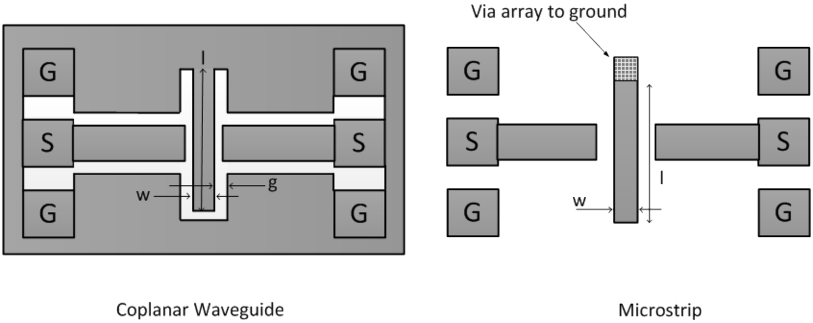

Fig. 6. Layout of short-circuited quarter-wavelength resonator geometries

A series of quarter-wavelength microstrip and CPW / GCPW resonators were tested with different ground plane levels, with the microstrip examples grounded with a 10 x 10 via array. The results are shown in Table 3.

Table 3. Unloaded Q-factors for quarter-wavelength resonators

Geometry	**Signal layer**	**Ground layer**	**Length (µm)**	**Width (µm)**	**Gap width (µm)**	Q_0
Microstrip	TM2	TM1	360	20	-	2.63
Microstrip	TM2	M1	410	45	-	11.71
CPW	TM2	-	360	30	20	10.55
GCPW	TM2	TM1	325	15	30	3.63
GCPW	TM2	M1	350	10	20	4.88

These simulated Q-factors for quarter-wavelength resonators are lower than the value of 15 estimated at W-band frequencies in [4] for dual-CPW (two stacked metal layers stitched together) resonators, but a comparable result is achieved using a single microstrip line grounded to M1. It is again shown that the placing the ground plane on M1 yields better resonator Q-factors than placing it on TM1, and that microstrip resonators generally provide higher Q-factors than CPW or GCPW. The feasibility of implementing resonators in a single CPW metallization layer is also highlighted in this geometry, with the CPW outperforming the GCPW resonators again.

Conclusion

This work presents, for the first time, a comparative study of the Q-factors obtainable with different planar resonator geometries at 94 GHz in a commercial BiCMOS BEOL process, with the effect of chip passivation included. It is shown that the obtainable Q-factors are lower than that achieved with equivalent geometries in V-band by approximately 75%, but that similar optimal geometrical proportions w.r.t. width and length, as well as choices of ground plane placement, are still valid. Straight half-wavelength microstrip and grounded microstrip quarter-wavelength resonators outperform hairpin and CPW / GCPW resonators by a significant margin, and future work will focus on these topologies for on-chip coupled resonator W-band filters in BiCMOS. Possible implementation of 94 GHz resonators in a single metallization layer with CPW hairpin and quarter-wave resonators is also demonstrated, and may find application in future GaAs / GaN designs where multiple metallization layers are not readily available.

Acknowledgements

The authors wish to thank ANSYS, Inc. and their channel partners in South Africa, Qfinsoft (Pty) Ltd, for providing the academic HFSS license used in this work. This work was further supported by the Eskom Tertiary Education Support Programme (TESP) and the associated Technology and Human Resources for Industry Programme (THRIP) grant № 90224.

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