High Quality Factor mm-Wave Coplanar Strip Resonator Based on Split Ring Resonators

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Abstract—**Coplanar strips (CPS) have the advantage of higher level of integration and a balanced structure that have favorable features for integrated voltage controlled oscillators and low noise and power amplifiers. Based on split ring resonator's (SRRs) rejection and phase shift properties around their resonance, a high quality factor composite right/left handed (CRLH) coplanar strips resonator is designed to operate in mm-wave regime at 60 GHz. Using this structure, a 52% improvement is achieved in comparison with an optimized conventional CPS resonator designed in a 90 nm CMOS process.**

I. Introduction

COMPARED to III-IV semiconductor technologies, such as GaAs, silicon CMOS technologies benefit from higher level of integration, higher scaling speed and lower cost [1]. With possibility of working at the 60 GHz license free band with recent sub-100 nm CMOS devices, there is a great interest in using CMOS technology in this frequency band [2], [3].

The main drawback of CMOS technology in the mm-wave regime is the fact that due to low resistivity of the silicon substrate, passive components suffer from substrate conductive loss, and as a result design of high quality factor passive components in this technology is a challenge. Due to their explicit distributed behaviors, among the passive components, transmission lines (TL) play a critical role in mm-wave MMIC design. TLs can be used not only to carry signals, but also can be used as reactive resonators in oscillators [4], [5], [6]. To modify TL frequency response, split ring resonators can be exploited.

The split ring resonator, originally proposed by Pendry [7], is a resonant element that is very small compared to the wavelength and can be excited by an external time varying magnetic field that is applied parallel to its ring axis. Due to the negative effective permeability of the medium in vicinity of the SRR's resonance frequency, SRR elements aligned with the CPS slot and placed in lower metal layers in MMICs are able to inhibit wave propagation in a narrow frequency range below or above the resonance frequency [8].

This paper demonstrates the design of high quality factor coplanar strip (CPS) resonator using SRRs in a 90 nm CMOS process, which is applicable in a 60 GHz oscillator.

II. Design of High Quality Factor SRR-Based Coplanar Strip Resonator

Generally, the resonance frequency of a conventional transmission line resonator is determined by its physical length. In fact, a conventional short ended TL converts into a quarter wavelength resonator if $\Delta\phi = \beta l = \pi/2$, where $\Delta\phi$ is the traveling wave phase delay, β is propagation phase constant and l is the physical length [9]. Obviously, with this criteria the traveling wave phase shift along a quarter wavelength resonator at the resonance frequency (f_r) is $\pi/2$ and for the waves at other frequencies (i.e $f_r + \Delta f$) phase shift has some deviation from $\pi/2$. In other words, assuming a TL loaded with Z_L the reflection coefficient at the input port is

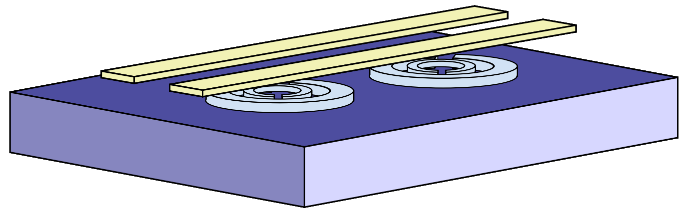

Fig. 1. SRR loaded high quality factor quarter wavelength resonator.

$$\Gamma_{\text{in}} = S_{11} + \frac{S_{12}\Gamma_{\text{L}}S_{21}}{1 - S_{22}\Gamma_{\text{L}}}, \quad (1)$$

where $S_{i,j}$ are the TL s-parameters and Γ_{L} is the load reflection coefficient [10]. For a reciprocal quarter wavelength short ended TL resonator, such as CPS resonator of this work, $S_{12} = S_{21}$ and $S_{11} = S_{22}$ and $\Gamma_{\text{L}} = -1$. So, the reflection coefficient at the input port is

$$\Gamma_{\text{in}} = S_{11} - \frac{S_{21}^2}{1 + S_{11}}. \quad (2)$$

This equation shows that for a resonator at resonance frequency, where Γ_{in} should be $1\angle 2k\pi$, $|S_{11}| = 0$ and $S_{21} = 1\angle 90°$ is one solution which is the case for a quarter wavelength short ended TL. Resonance occurs at a frequency where the Γ_{in} phase is $0°$. For the frequencies either higher or lower than f_r, $\angle\Gamma_{\text{in}} \neq 0°$. The main point is that the resonator's quality factor is determined by the rate of deviation of $\Gamma_{\text{in}}(f)$ from $\Gamma_{\text{in}}(f_r)$. For a conventional $\lambda/4$ short ended TL, Γ_{in} phase, changes linearly with frequency.

With the above mentioned point in mind, since the resonator's quality factor is directly proportional to the deviation rate, the quality factor issue in TL resonators in CMOS technology can be addressed by using SRRs to increase the deviation rate around the resonance frequency and consequently increasing the quality factor.

As shown in Figure 1, the proposed structure is composed of a short ended conventional CPS as a balanced quarter wavelength resonator and SRRs to improve the resonator's quality factor. The CPS resonator, without the SRRs is designed to

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operate at 60 GHz, and the SRRs are symmetrically laid out below the slot between the CPS strips to obtain high inductive coupling at resonance [11].

In order to achieve a high-Q SRR based CPS resonator, the introduced SRRs were tuned to resonate at 65 GHz. According to (2), the rejection band caused by SRRs leads to increased phase and amplitude deviation rate of the Γ_{in} at frequencies above the resonance frequency.

Figure 2 compares the normalized input impedances for a conventional CPS resonator from [6], a conventional CPS resonator as host TL for SRRs and the proposed high quality factor SRR loaded resonator. The conventional CPS resonator from [6] was optimized to operate as a high quality factor resonator at 60 GHz. From this figure it is clear that the proposed resonator has a narrower -3 dB bandwidth compared to the conventional ones, which implies a higher quality factor.

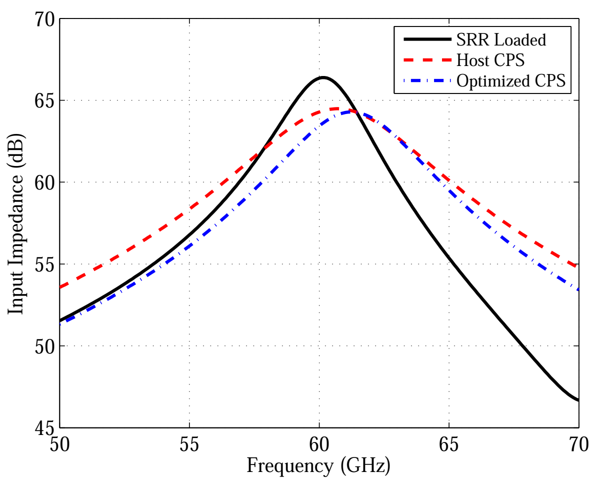

Fig. 2. Impedance of the optimized conventional and SRR-based quarter wavelength CPS resonators. Impedances are normalized to $1\,\Omega$.

Table I also compares the quality factor, length, and input impedance of the three types of CPS resonators. The reference for the comparison is the simulated characteristics of the optimized conventional CPS resonator from [6]. This resonator has a length of $625\,\mu\text{m}$ to resonate at 60 GHz and has a quality factor of 11.6, spacing $S = 6\,\mu\text{m}$ and width $W = 6\,\mu\text{m}$. The second resonator in the table is a conventional CPS resonator with spacing $S = 60\,\mu\text{m}$ and width $W = 20\,\mu\text{m}$, which is used as host TL for SRRs. This TL is designed to resonate at 60 GHz and it has a length of $600\,\mu\text{m}$ and quality factor of 9. Table I also shows the characteristics of the proposed resonator which is basically the second resonator loaded with SRRs. It has a length of $490\,\mu\text{m}$ resonating at 60 GHz and it has a quality factor of 17.7, which shows 52% improvement in quality factor. Although the proposed resonator has a wider layout than the reference resonator, it has advantages of much higher quality factor, better aspect ratio and shorter length. The proposed resonator also shows 2 dB improvement in normalized input impedance at resonance. This high input impedance results in lower bias current of the oscillator, which implies lower power consumption.

TABLE I
COMPARISON OF Q-FACTOR, RESONANCE FREQUENCY AND LENGTH OF DIFFERENT TYPES OF QUARTER WAVELENGTH CPS RESONATORS.

Resonator Type	Length (μm)	f_0 (GHz)	Q-factor	Q-factor Improvement
Conventional [6]	625	61	11.6	reference
Host TL without SRRs	600	60	9	-22%
SRR loaded (this work)	490	60	17.7	+52%

III. Conclusion

Using full-wave 3D EM simulation, a high quality factor CPS resonator operating at 60 GHz has been designed. The proposed structure has been designed using standard 90 nm CMOS process parameters. Quality factor of this novel resonator is 17.7 which is a 52% improvement in quality factor compared to the optimized conventional CPS resonator ($Q = 11.6$) operating at the same frequency. It also shows 2 dB improvement in normalized input impedance at resonance, which results in lower bias current of the oscillator and consequently lower power consumption.

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