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<th>80GHz on-chip metamaterial resonator by differential transmission line loaded with split ring resonator</th>
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An on-chip metamaterial resonator is demonstrated in 65 nm CMOS at 80 GHz for millimetre-wave integrated circuit (MMIC) applications. The resonator is based on a differential metamaterial transmission-line (T-line) loaded with a split ring resonator (SRR), which can enhance the EM energy coupling and further improve the quality factor (Q). Measurement results indicate that the proposed differential SRR (DSRR) T-line shows a sharp stopband with maximum 35 dB rejection. Moreover, the metamaterial property of the DSRR T-line is validated from the measurement results. It is the first on-chip demonstration of a millimetre-wave metamaterial resonator in 65 nm CMOS, which can be integrated for a low-noise oscillator and high-Q filter design in a 100 GHz MMIC communication system.

Introduction: With the scaling down of CMOS technology in recent years, CMOS millimetre-wave integrated circuits (MMICs) are being feasibly realised for high data rate communication systems. In the millimetre-wave operation regime, owing to the passive device loss in substrate and metal interconnection, the quality factor (Q) of the resonator based on an LC-tank or transmission line (T-line) suffers from serious degradation, which can lead to high phase noise of voltage-controlled oscillators (VCOs).

To improve the Q of the resonator, metamaterial T-line based resonators have been explored recently for CMOS MMIC applications. Metamaterial with negative permittivity ($\epsilon$) and permeability ($\mu$) has drawn attention recently. Split ring resonator (SRR) structures are those demonstrations implemented on a printed circuit board (PCB) with operating frequencies below 10 GHz [1]. An on-chip single-ended metamaterial T-line based on an SRR was proposed for 60 GHz MMICs applications but without chip demonstration [2]. In the SRR-loaded T-line, the resonant property is mainly determined by the SRR which behaves as a metamaterial.

Note that the SRR can be deployed for a resonator within a diameter less than 1 mm
when operated in the millimetre-wave region. In this Letter, a differential SRR (DSRR) T-line is proposed to improve the Q of the resonator from two perspectives: 1. strong magnetic coupling enhances EM energy transferring between the T-line and the SRR; and 2. a differential design with floating metal shielding reduces the substrate loss. Thus, the DSRR T-line resonator design in this Letter shows a high Q property with high rejection (-35 dB).

**Previous design of on-chip SRR:** Originally demonstrated by Pendry et al., SRRs are high-Q sub-wavelength resonators [3]. Fig. 1a shows the basic topology of the rectangular SRR. When excited by a magnetic field parallel to the z-axis, the SRR shows negative μ and positive ε around the resonance frequency. This metamaterial property inhibits signal propagation in a narrow band around the resonant frequency. As shown in Fig. 1b, the SRR externally driven by an axial magnetic field operates as an LC resonant tank in a narrow band with effective inductance $L_s$ and capacitance $C_s$.

The on-chip SRR can be implemented in a stacked fashion with an on-chip multi-layer interconnection [2]. As shown in Fig. 2a, one SRR unit-cell is realised by the top two metal layers stacked alternatively, considering a trade-off among resonant frequency, area and loss. When its size is fixed, the SRR is simulated in terms of $S_{21}$ with different stacked layers. As shown in Fig. 2b, more stacked layers result in a lower resonant frequency, but suffer from lower Q simultaneously. With increased resonant frequency, the SRR reveals a higher rejection property, which means a higher Q due to the lower loss in the resonator. The larger sizes of $R_1$ and $R_2$ in Fig. 1a result in the lower resonant frequency. The distance between the two rings and the gap of the ring are reduced to lower the resonant frequency. Then, the target resonant frequency can be achieved with high area-efficiency and low loss.

**Proposed high-Q DSRR T-line:** The limitations of previous designs are as follows. The on-chip single-ended T-line with a SRR in [2] consumes large area and has weak coupling strength, which leads to a low Q. Furthermore, the single-ended T-line is no longer adequate for the circumstances of the widely-used differential circuit design in MMICs. In this Letter, a differential SRR (DSRR) T-line is proposed as shown in Fig. 3a. The two loaded SRR unit-cells are excited by the axial magnetic field generated by the host T-line. First, as the SRR load is high-Q metamaterial at resonant frequency, it shows stopband property and hence EM energy can be perfectly reflected to the host T-line. Secondly, compared with the on-chip singed-ended T-line with a loaded SRR in [2], the differential one in this Letter can further enhance Q and reduce loss. For example, the magnetic field generated by the differential T-line is equidirectional and superimposed when applied to the two SRR unit-cells. Thus, a stronger coupling between the T-line and the SRR can be achieved with larger mutual capacitance and mutual inductance, which can store more EM energy with less EM energy leakage into the substrate. To strengthen the coupling between the T-line and the SRRs, a shortest distance between the SRRs and the T-line is selected with
consideration of the process limitation (1.5 μm in STM 65 nm CMOS). Moreover, floating metal shielding is employed to reduce substrate loss as well in the millimetre-wave region, which further improves the Q.

In addition, note that different from the traditional T-line resonator [4], the resonant frequency of the DSRR T-line resonator is determined by the SRR which has metamaterial behaviour, but not by the length of the T-line. Under the same resonant frequency, the stacked SRR usually has more compact implementation for the effective inductance and capacitance. As such, our DSRR T-line occupies much smaller area and has lower loss and higher Q than the traditional T-line.

**Experimental results:** The proposed DSRR T-line resonator was fabricated in STM 65 nm CMOS process. Fig. 3b shows the chip photo. The core area is 140 × 150 μm excluding pads. The optimisation of this structure is conducted with the full-wave EM simulator Agilent Momentum. The stacked SRR unit-cell is designed by the top two metal layers (M7, M6). M7 and M5 are used for the design of the host T-line and the floating metal strips for shielding, respectively. The sizes of the T-line, the SRR and the floating metal strips are carefully selected to obtain the desired frequency and rejection property. The designed parameters are marked in Fig. 1a and Fig. 3a.

The scattering parameters were measured on a Cascade Microtech Elite-300 probe station using Agilent PNA-X (N5247A) with frequency sweeping up to 110 GHz. The testing pads and traces are de-embedded from both sides of the T-line with recursive modelling technique. As shown in Fig. 4a, the measurement results agree well with the EM simulation, the small discrepancies are due to process variations and high dissipative losses not considered in the simulation at high frequency. The measurement results show that the DSRR T-line resonator exhibits a sharp stopband with maximum 35 dB rejection. To validate the metamaterial property of the DSRR T-line resonator, the effective ε and μ are further extracted from the measurement results. We convert the scattering parameters to determine refractive index n and impedance z [5], which are given by

\[ n = \frac{1}{k_0d} \cos^{-1} \left[ \frac{1}{2S_{21}^2} (1 - S_{11}^2 + S_{21}^2) \right] \]  
\[ z = \frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2} \]

where \( k_0 \) is the free space wave number and \( d \) is the unit-cell size. Then effective ε and μ can be calculated as follows:
\[ \varepsilon_{\text{eff}} = \frac{n}{z}, \quad \mu_{\text{eff}} = n \times z \]  

(3)

For the passive component, it is required that $\text{Re}(z) > 0$ and $\text{Im}(n) < 0$ [6]. As shown in Fig. 4a, the impedance of the proposed differential structure is further calculated from the singled-ended S-parameter measurement based on the mixed-mode characterisation [7]. As a result, the resulting resonant frequency is found at 80 GHz for the DSRR T-line resonator. Moreover, as shown by (1)–(3) and Fig. 4b, the retrieved data from the singled-ended S-parameter measurement confirms the metamaterial property of effective negative $\mu$ and positive $\varepsilon$ in the resulting stopband. Note that the SRR used in this Letter is for high-Q resonator application due to the introduced sharp stopband for the perfect EM-wave reflection to form resonance. As such, one can build a compact and high-Q VCO in the MMIC design.

**Conclusion:** An on-chip differential SRR (DSRR) T-line based meta-material resonator was implemented in 65 nm CMOS. Owing to the strong EM energy coupling between the host T-line and the loaded SRR, one can observe a high Q resonant behaviour at the resonant frequency. The differential implementation with floating metal shielding reduces the substrate loss and further increases the Q. As shown in the measurement results, a sharp stopband with maximum 35 dB rejection is achieved. This feature supports the realisations of a low-noise oscillator and a high-Q filter in a 100 GHz MMIC communication system.

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