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A 75.7GHz to 102GHz Rotary-traveling-wave VCO by Tunable Composite Right /Left Hand T-line

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Abstract—With the use of tunable composite-right/left-hand (CRLH) transmission line (T-line), this paper provides a wide frequency-tuning-range (FTR) mechanism for Mobius-ring rotary-traveling-wave (RTW) VCO in millimeter-wave region. CRLH T-line is implemented in RTW-VCO with inductor-loaded transformer to realize sub-band selection over a wide FTR. Each sub-band is further covered by a varactor for fine-tuning. The chip was fabricated in GF 65nm RF-CMOS process with area of 0.08mm². The measured results show a current consumption of 14mA under supply voltage of 1V, a tuning range of 29.5% with center frequency at 89.3GHz, and a phase noise from -100.08dBc/Hz to -98.7dBc/Hz with 10MHz offset. A state-of-art figure-of-merit FOM_T of -177.78dBc/Hz is demonstrated.

I. INTRODUCTION

Many big-data communication and imaging applications have been recently demonstrated by CMOS based millimeter-wave integrated circuits (MMICs) [1-6]. Multi-phase and quadrature oscillators are essential building blocks in these applications, which are normally realized by traveling wave to generate multi-phase clock outputs with good phase noise performance [5-8]. Mobius-ring rotary-traveling-wave (RTW) VCO topology is commonly adopted due to its advantages such as easy placement of cross-coupled transistors, good matching of differential blocks and compact area [8].

Traditionally, RTW-VCO is implemented with conventional right-handed (RH) transmission line (T-line), with a phase delay directly proportional to the T-line physical length [7-9]. Since a total phase delay of 360-degree is required to for oscillation, a large area is induced. Recently, left-handed (LH) T-line has shown to provide a superior performance at high frequency [10], and also unique features such as nonlinear dispersion curve [11]. Due to large parasitic capacitors from cross-coupled transistors that are RH in nature, the actual implemented T-line is a composite right/left hand (CRLH) T-line. By merging the phase shifts from LH and RH components together, CRLH T-line provides a phase delay independent of its physical size, and thus can be designed to be much more compact than conventional RH T-line for VCO.

As big-data communication or imaging applications require a wideband to ensure high data rate and also to cover process variation by CMOS MMIC at advanced technology, tuning ability of RTW-VCO has not been thoroughly studied and achieved as far. Conventional RTW-VCO is mostly tuned by varactor and capacitor bank due to the RH topology [7-9]. Due to constraint tuning ability of varactor and capacitor bank

Fig. 1. CRLH T-line based Mobius-ring RTW-VCO.

in millimeter-wave region, the achieved FTR is quite limited [7-9]. CRLH T-line, on the other hand, provides more choices of tunable elements to achieve a wide FTR in RTW-VCO design, but is not well explored at millimeter-wave region [10]. In this work, a tunable CRLH T-line is studied for RTW-VCO to achieve wide FTR.

The paper is organized as follows. Section II presents the design and analysis of the tunable CRLH T-line based RTW-VCO. A VCO prototype is designed with measurements results in Section III and conclusions in Section IV.

II. TUNABLE CRLH T-LINE BASED RTW-VCO

A. CRLH T-line based RTW-VCO

The topology for Mobius-ring RTW-VCO is shown in Fig. 1. A Mobius-ring is evenly divided into N stages, with each stage loaded with a cross-coupled transistor pair. As wave travels along the Mobius-ring, certain phase delay must be fulfilled to create a positive feedback for VCO oscillation. At the same time, cross-coupled transistors should generate enough power to compensate the loss from the T-line. In summary, the start-up condition of Mobius-ring RTW-VCO is

$$g_m > \frac{2\exp(-\alpha l)}{z_o}; \beta l = \frac{M\pi}{N}. \quad (1)$$

where g_m is the transconductance of the cross-coupled pair, z_o , l , α , β are T-line characteristic impedance, physical length, attenuation constant, and phase constant, respectively. N is the stage number, and $M=\pm 1, \pm 3, \dots$ is an odd integer number.

In this work, CRLH T-line is deployed in the Mobius-ring RTW-VCO for compact size. CRLH T-line is one kind of metamaterial that is composed of LH and RH components [12-13] with equivalent circuit of one unit-cell shown in Fig.1. Serial capacitors (C_s) and parallel inductors (L_p) form its LH portion with a negative phase constant (β_L), while parallel capacitors (C_p) and serial inductors (L_s) form its RH portion with a positive phase constant (β_R). With a balanced design ($C_s \cdot L_s = C_p \cdot L_p$), phase constant for CRLH T-line can be simplified as

$$\beta = \beta_R + \beta_L = \omega \sqrt{L_s C_p} - \frac{1}{\omega \sqrt{L_p C_s}}. \quad (2)$$

Note here all components (L_s , L_p , C_s , C_p) are normalized with respect to the unit-cell length.

With (1) and (2), the oscillation frequency for an N -stage Mobius-ring RTW-VCO by CRLH T-line can be obtained

$$\omega_{CRLH} = \frac{\pi}{2Nl\sqrt{L_s C_p}} \times \left(\sqrt{1 + \frac{4N^2 l^2}{\pi^2} \sqrt{\frac{L_s C_p}{L_p C_s}}} \pm 1 \right). \quad (3)$$

Here only the fundamental resonant condition $M=\pm 1$ is considered for simplicity of illustration. The plus and minus signs in (3) correspond to CRLH T-line working in the RH region and LH region, respectively.

What is more, phase noise is an important specification for VCO design. Generally, for N -stage RTW-VCO, the phase variation $\langle \Phi^2(t) \rangle$ is proportional to $1/N$ [7, 14-16], which is reduced by $1/N$ when compared to single stage.

In this work, the LH operation is selected for compact size and superior performance when implemented in multiple stages [10]. However, there is no study on how to tune the CRLH T-line based RTW-VCO, which will be addressed in the next part.

B. Wideband tuning for CRLH T-line based RTW-VCO

Note that in (3), there are 4 components that may be used for tuning: L_s , L_p , C_s , C_p . For easy analysis, we represent the product of the LH components ($L_p C_s$) as P_L ; and represent the product of the RH components ($L_s C_p$) as P_R . Then, the oscillation frequency in the LH region becomes

$$\omega_{CRLH_LH} = \frac{\pi}{2Nl\sqrt{P_R}} \times \left(\sqrt{1 + \frac{4N^2 l^2}{\pi^2} \sqrt{\frac{P_R}{P_L}}} - 1 \right). \quad (4)$$

Conventionally, P_R is used to realize FTR by varactor as part of C_p [10]. Unfortunately, with the omitted L_s component and thus small P_R value in [10], the tuning ability by P_R is very limited, not to mention the already constraint tuning ability as well as the limited quality factor of varactor at high frequency. In fact, for a small P_R / P_L value, ω_{CRLH_LH} approaches the operation frequency of a pure LH T-line based RTW-VCO

$$\omega_{CRLH_LH} \Big|_{\frac{P_R}{P_L} \rightarrow 0} = \omega_{LH} = \frac{Nl}{\pi \sqrt{P_L}} \quad (5)$$

Fig. 2. (a) Equivalent circuits of an inductor-loaded transformer with the loaded switches. (b) Layout implementation for inductor-loaded transformer where tuned inductance is determined by states of two switches

which is independent of P_R with poor tuning ability.

Intuitively, a wider FTR should be obtained by tuning P_L since the LH-components dominate in the LH region. Since $\frac{\delta \omega_{CRLH}}{\delta P_L}$ stays positive for all P_L values, the FTR can be calculated

$$\Delta \omega_{CRLH_LH} = \frac{\pi}{2Nl\sqrt{P_R}} \times \left(\sqrt{1 + \frac{4N^2 l^2}{\pi^2} \sqrt{\frac{P_R}{P_{L_min}}}} - \sqrt{1 + \frac{4N^2 l^2}{\pi^2} \sqrt{\frac{P_R}{P_{L_max}}}} \right). \quad (6)$$

The extreme condition forms for a pure LH T-line with

$$FTR_{LH} = \frac{\frac{1}{\sqrt{P_{L_min}}} - \frac{1}{\sqrt{P_{L_max}}}}{\frac{1}{\sqrt{P_{L_min}}} + \frac{1}{\sqrt{P_{L_max}}}} \times 2 \approx \frac{\alpha_{P_L}}{2} \quad (7)$$

where $\alpha_{P_L} = \frac{\delta P_L}{P_L}$ measures the tunability of components in P_L .

As (7) shows, FTR_{LH} is directly proportional to α_{P_L} .

However, since the loss in C_s adds directly into the signal path, it is not feasible to tune C_s . On the other hand, one can realize a wide FTR by tuning L_p with a loaded transformer structure [4]. More specifically, inductive-loaded transformer can achieve a large α_{P_L} , which is adopted in this work.

The mechanism for inductive-loaded transformer can be explained in Fig. 2(a), where a transformer is loaded with switch on its secondary coil. By turning the switch on or off, the equivalent inductance (L_{eq}) looking into transformer primary coil can be effectively changed as:

$$\begin{cases} L_{eq_on} = L_1 - \frac{\omega^2 M^2 L_2}{(R_2 + R_{on})^2 + \omega^2 L_2^2} \approx (1 - k^2) L_1 \\ L_{eq_off} = L_1 + \frac{\omega M^2 (\frac{1}{\omega C_{off}} - \omega L_2)}{R_2^2 + (\frac{1}{\omega C_{off}} - \omega L_2)^2} > L_1 \end{cases} \quad (8)$$

Fig. 3. Tuning mechanism for the proposed tunable CRLH T-line based Mobius-ring RTW-VCO: (a) Equivalent circuit, (b) Dispersion diagram.

where L_{eq_on} and L_{eq_off} represent different L_{eq} values when the switch is turned on or off, respectively. L_1 , L_2 , M , and k are transformer primary, secondary, mutual inductances, and coupling factor. The loss of transformer is represented by two serial resistances R_1 and R_2 . Equivalent circuits for the switch during its on and off states are modeled by a resistor R_{on} and a capacitor C_{off} , respectively. As (4) indicates, a large α_{PL} can be easily obtained by implementing a large coupling factor k for the transformer. Moreover, since the tuning element is not directly included in the signal path, the phase noise degradation is low. What is more, multiple inductors can be switched on and off to further increase α_{PL} with a wide FTR achieved by creating multiple sub-bands.

The designed switched coupled-inductor for inductive tuning is shown in Fig. 2(b). Inductors are realized by the top Cu layer to guarantee a high quality factor. Two transformers loaded with two switches are used to realize 4 sub-bands. As summarized in the tables shown in Fig. 2(b), the resulted L_{eq} can be varied over a large range from 47pH to 91pH. As such, wide FTR can be realized with 4 sub-bands: (75.67-83.11GHz), (79.65-87.78GHz), (86.18-94GHz) and (93.89-102.01GHz). To realize a continuous tuning, fine-tuning by varactor is used in each sub-band. To increase the tuning ability of varactor as (5) indicates so as to fully cover each sub-band, a relatively large L_s value is adopted in this design.

The resulted tuning mechanism for the proposed CRLH T-line based RTW-VCO can be explained in Fig. 3. Inductive-loaded transformer creates multiple sub-bands by shifting the dispersion curve to different resonant frequency points. Each sub-band is then covered with fine-tuning by a varactor.

III. VCO IMPLEMENTATION AND MEASUREMENT

Fig. 4(a) shows the on-chip implementation for the proposed tunable CRLH T-line based Mobius-ring RTW-

Fig. 4. (a) Die micrograph of the proposed VCO. (b) The EM simulation for one CRLH T-line unit-cell. Note that L_p is shared by two unit-cells and its value is purposely designed doubled.

Fig. 5. Measured frequency tuning range by 4 sub-bands.

VCO. To push the cut-off frequencies away from operation frequency region, each stage is implemented with 2 distributed CRLH T-line unit-cells. As a result, 180-degree phase shift is required due to the Mobius-ring connection, which leads to a 90-degree phase shift in each unit-cell. The EM simulation results for the designed unit-cell are shown in Fig. 4(b). At the frequency of interest 100GHz, one unit-cell can provide 90-degree phase-shift with loss at -1.86dB, which is compensated by the negative resistors realized by a cross-coupled pair. Note the unit-cell is biased to operating in the LH region, with the resonant mode in the RH region (-90-degree phase shift) highly suppressed.

The proposed VCO is fabricated 65nm CMOS Global Foundries 1P8M RF CMOS process. The VCO core area is about 0.0812mm². The output spectrum is measured by E4408B spectrum analyzer through one 11970W harmonic

Fig. 6. Measured phase noise at 82.22GHz center frequency with 10 MHz offset frequency

Fig. 7. Measured output power across the entire frequency tuning range.

TABLE I. PERFORMANCE SUMMARY AND COMPARISON

Parameters	[1]	[2]	[3]	This Work	Unit
f_{osc}	95.7	101	70.4	89.3	GHz
VDD_{core}	1.5	0.8	1.2	1	V
P_{DC}	9	11.9	5.4	14	mW
Phase Noise (PN) @10MHz	-106	-104.5	-106.1	-100.8	dBc/Hz
FTR (%)	3.6	11.2	9	29.6	%
FOM _T	-167.1	-176.5	-175.4	-177.8	dBc/Hz
Tech.	CMOS 65	CMOS 65	SOI CMOS 65	CMOS 65	nm

$$FOM_T = PN - 20 \log \left(\frac{f_{osc}}{\Delta f} \times \frac{FTR}{10} \right) + 10 \log (P_{DC}/1mW)$$

mixer. The supply voltage for buffer is 1.2V and for VCO is 1V. The measured current for the core VCO is 14mA. As shown in Fig. 5, by using the proposed tunable CRLH-T-line, a wide FTR of 29.6% is achieved from 76.59GHz to 102.01GHz, with a center frequency at 89.33GHz. The full FTR is formed from the four sub-bands controlled by two switches: (75.67-83.11GHz), (79.65-87.78GHz), (86.18-94GHz) and (93.89-102.01GHz). With a tuning voltage for varactor from 0V to 1.2V, each sub-band is fully covered. The measured phase noise varies from -100.08dBc/Hz to -98.7dBc/Hz with a sample plot shown in Fig. 6. The measured output power is from -23dBm to -15dBm as shown in Fig. 7. The output power variation is about 8dBm.

As summarized in Table I, the performance of the proposed VCO is further compared with other published millimeter-wave VCOs in 65nm CMOS technology. According to the Table I, the phase noise is comparable with others, and the widest FTR and the best FOM_T are achieved by the proposed VCO.

IV. CONCLUSION

A tunable CRLH T-line based millimeter-wave Mobius-ring RTW-VCO has been demonstrated in this paper with a wide FTR of 75.7-102GHz. Inductor-loaded transformer is implemented in CRLH T-line to realize 4 sub-bands. Each sub-band is covered by a varactor with fine-tuning. The proposed tunable CRLH T-line based RTW-VCO is fabricated in 65nm GF RF-CMOS process with area of 0.0821mm². The measured results show a current consumption of 14mA under supply voltage of 1V, a FTR of 29.5% with center frequency at 89.3GHz, and a phase noise of -100.8dBc/Hz with 10MHz offset at 82.2GHz center frequency. The state-of-art figure-of-merit FOM_T is demonstrated at -177.78dBc/Hz.

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