EM Analysis of Rotary Travelling Wave Oscillator Topology

Marvin Aidoo[1], Jonathan Matson[1] ,Huseyin Savci[2], Zhijian Xie[1], and Numan S. Dogan[1]

[1]Electrical and Computer Eng. Dept.
North Carolina Agricultural & Technical State University
Greensboro, NC, USA
maidoo@ncat.edu, matsonjl@gmail.com,zxie@ncat.edu, dogan@ncat.edu

[2]Department of Computer Engineering
Istanbul Sabahattin Zaim University
Istanbul, TURKEY
hssavci@syr.edu

Abstract: Rotary travelling wave oscillator (RTWO) represents a new transmission line based technology for multi-gigahertz clock generation. In its operation, the forward travelling wave is amplified while the backward wave is attenuated to achieve low phase noise. In this paper, we demonstrate the mechanism to effectively attenuate the backward wave for low phase noise performance. In order to obtain a good performance measure in terms of phase noise, one needs to pay attention to the on-resistance of the cross-coupled inverter pair for RTWO.

Keywords: RTWO, Cross coupled inverter pair, phase noise

1. Introduction

Rotary Traveling Wave Oscillator (RTWO), first introduced as a new transmission line approach for gigahertz-rate clock generation [1], has witnessed designs in different frequencies from hundreds of MHz to about 50 GHz. Compared with L-C tank oscillators and other wave-based oscillators, RTWO is not susceptible to mismatches due to its unique crossover reverse feedback segments. Performance of RTWO matches with other designs including low power consumption and accurate frequency. Due to the topological symmetric nature of the RTWO, the wave rotary direction has been attributed to uncontrollable factors such as initial symmetric breaking and least resistance path [1-4]. The basic RTWO architecture is a Mobius-ring-like transmission line with cross-coupled inverter pairs distributed along its path as shown in Fig.1 (a). The transmission line works in odd mode regime imposed by cross-coupled inverter pairs (CCIPs) with signal voltages on the same positions having 180^{o} phase difference. In addition to imposing the odd mode operations for the differential line, CCIP sustains the oscillations and replenishing the energy loss in the transmission line. In this paper, SONNET RF design tool is used to study various characteristics of RTWO. Section 2 studies resonant and Ohmic characteristics of RTWO. Section 3 discusses simulation results and Section 4 concludes the paper.

2. Analysis and Simulation

A. Resonant Characteristcs

This work was supported by National Science Foundation under grant ECCS 1129053

For the purpose of analysis, the entire structure can be analyzed as segments of resonators cascaded together in series. Fig. 1(b) shows the basic RF model of a short segment of RTWO line with main components and parasitics annotated. RTWO can be viewed as a superposition of multiple quarter-wave-length (λ/4) Standing Wave Oscillators [5].

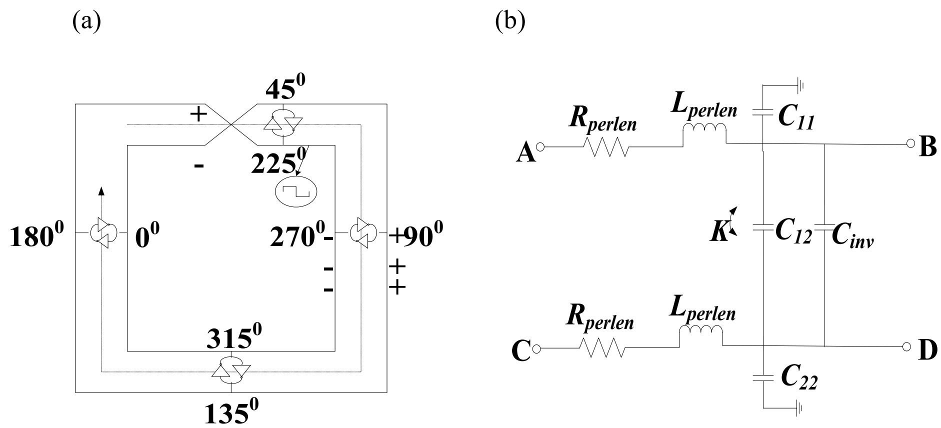

Fig.1. (a) RTWO structure; (b) RF macro-model of one short segment.

B. Ohmic Characteristics of Cross-coupled Inverter pair

Cross-coupled inverter pair is the basic amplification unit for the RTWO. It is crucial to understand the interaction between CCIP and the propagating wave on the transmission line. CCIPs distribute along RTWO transmission line. Previous CCIP stage will force a mostly differential signal to the following CCIP.

We use V_A, V_B, I_A, I_B representing the potentials and currents at the two ends of CCIP. In the differential mode, the following relations hold: $V_A+V_B=V_{DD}$ and $I_B = - I_A$. Let V_{TN} and V_{TP} represent the absolute value of threshold voltage of NMOS and PMOS respectively. When $V_A<V_{TN}$, PMOS in linear region and NMOS in off-state. When $V_A> V_{DD} -V_{TP}$, NMOS in linear region and PMOS in off-state. When V_A is in between V_{TN} and $V_{DD} -V_{TP}$, the net current is the drain current difference between PMOS and NMOS. Based on these relations, the DC current of CCIP in odd mode operation can be derived from linear and saturation current equations as:

$$I_B = \begin{cases} K_p(V_{DD} - \frac{3}{2}V_A - V_{TP})V_A, & V_A < V_{TN} \\ \frac{K_p}{2}(V_{DD} - V_A - V_{TP})^2 - \frac{K_n}{2}(V_A - V_{TN})^2, & V_{DD} - V_{TP} > V_A > V_{TN} \\ -K_n(V_{DD} - \frac{3}{2}V_B - V_{TN}) \cdot V_B, & V_A > V_{DD} - V_{TP} \end{cases} \quad (1)$$

Fig. 2 shows the current versus differential voltage relationship. It identifies three regions of operation. Regions 1 and 3 represent positive resistance regions where the inverter pair behaves as a shunt Ohmic resistor. Region 2 represents the negative resistance region where the inverter pair amplifies the input differential signal. This is the nonlinear nature of the CCIP, which presents different effects for forward and backward waves. Backward waves have small amplitude and attenuated by shunt Ohmic resistance. Meanwhile, forward wave forces CCIP to enter region 2 to be amplified.

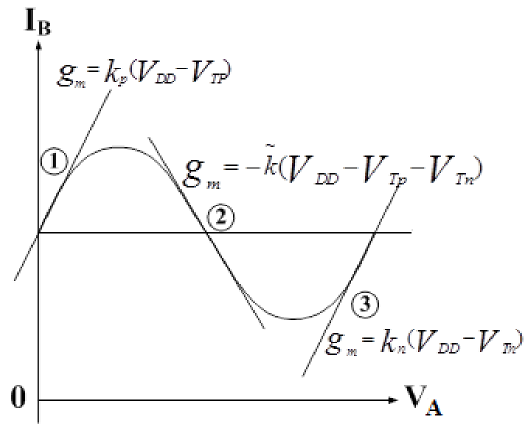

Fig. 2. DC transfer characteristics of the cross-coupled inverter pair to a differential signal.

For the CCIP, it is reasonable to assume that the NMOS and PMOS transistors have the same trans-conductance parameters (properly sized transistors, that is, $K = K_n = K_p$). This ensures the symmetric I-V response as shown in Fig 2. The negative conductance in region 2 is given by [6]:

$$g_m = -K \cdot (V_{DD} - V_{TP} - V_{TN}) / 2 \tag{2}$$

It must be noted that the elements in an extracted view of an RTWO design are not uniformly distributed. As a result, backward propagating wave generation is inevitable due to the reflections and the overshoots during state flipping. Thus it is worthwhile to investigate backward wave propagation in details.

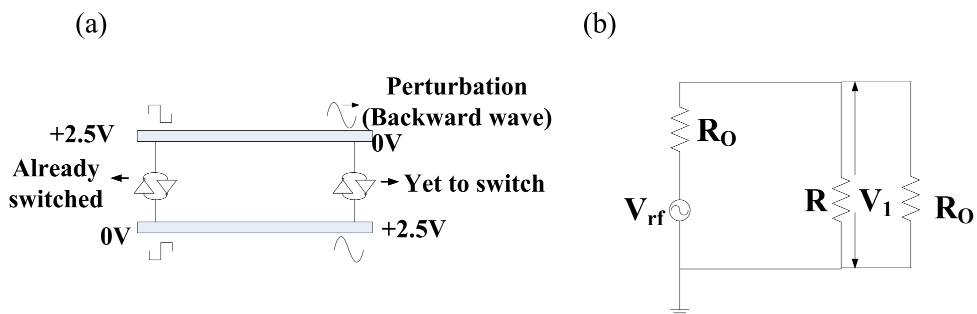

Fig. 3. (a) RTWO segment showing backward wave [1] ; (b) Circuit model for backward wave analysis.

The transmission line is uniformly distributed by design. However, mismatches along the line are introduced by shunt Ohmic resistances of the inverter pairs. Fig. 3 shows one segment of RTWO and a circuit model for analysis of the attenuation for backward waves.

In Fig. 3(b), V_{rf} stands for the voltage source due to backward wave. R_o is the internal resistance of the voltage source which matches with the characteristic impedance of the line. R is the shunt resistance presented by cross-coupled inverter pair (CCIP) seen by backward wave and V_1 is the voltage across R. The wave power is given by the following relation:

$$P_{rf} = V_{rf}^{\ 2} \big/ 8R_o \tag{3}$$

The power dissipated by the resistance of CCIP for backward wave is deducted as the following:

$$V_1 = \frac{R//R_o}{R_o + R//R_o} V_{rf} = \frac{V_{rf}}{R_o/R+2} \Rightarrow P_{rf}' = \frac{V_1^2}{2R} = \left(\frac{1}{R_o/R+2}\right)^2 \times \frac{Vrf^2}{2R} \Rightarrow \frac{P_{rf}'}{P_{rf}} = \frac{4(R_o/R)}{(R_o/R+2)^2} \qquad (4)$$

where P_{rf}' is the thermal dissipated power for backward wave. From above, it can be further deducted that there is a maximal ratio (=50%) can be reached when $R_0=2R$. Since the backward wave is one of the primary sources of phase noise and disturbance, the on-resistance of CCIP should present about half of the line impedance value to minimize the disturbance. To be noted, CCIP enters the amplification stage for forward wave where the effective R has negative values.

3. Simulation and Result Discussion

To determine the resonant properties of RTWO ring topology, SONNET RF design tool is utilized to analyze its S-parameter and current density. The 2.4GHz RTWO has been designed as shown in Fig. 4(a). Shunt resistors have been distributed to represent the on-resistance of CCIP during non-amplification stages. Fig. 4(b) shows the currents distribution and Fig. 4(c) shows the reflection coefficient (S_{11}) for the on-resistance equal to 1Ω, 15 Ω, 25 Ω, 50 Ω and infinite. RTWO with R=25 Ω presents a broad band low reflection coefficients, while the RTWO with high R values show narrow band resonance and the one with low R values reflect most power back.

(a) (b)

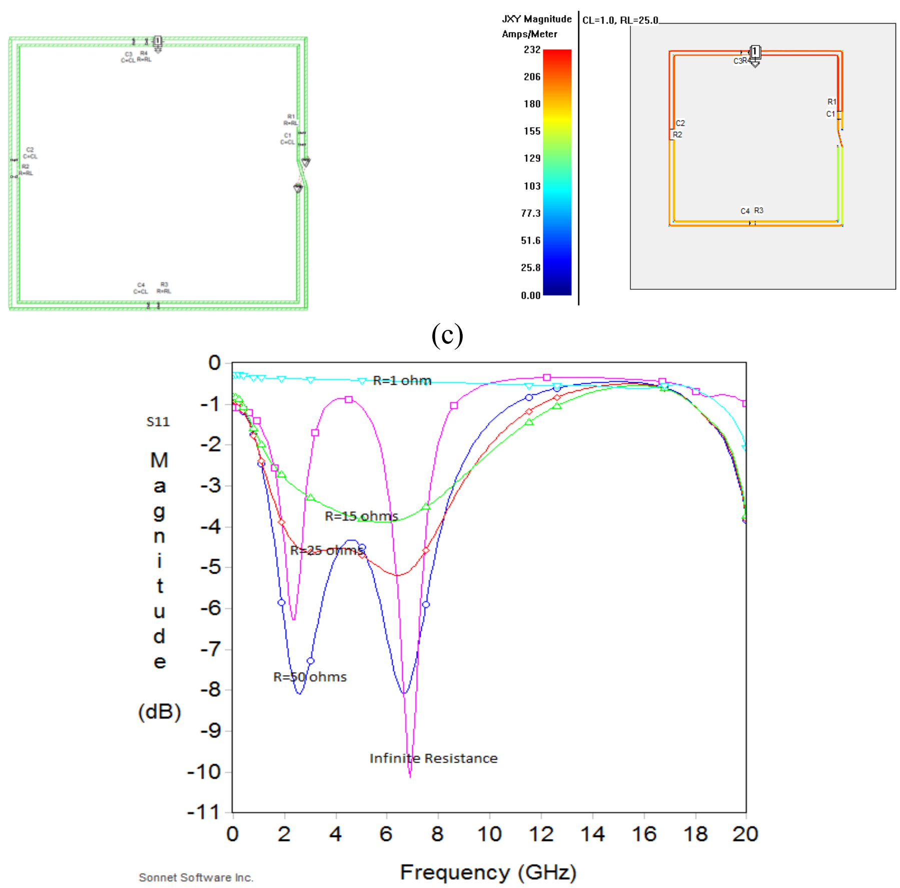

Fig. 4. (a) RTWO Structure ; (b) current density at 2.4GHz for R=25Ohm; (c) S11 for various ohmic shunt resistances.

Fig. 5 shows the far field data to confirm low radiation from RTWO structures. Under this condition, RTWO with R=25 Ω dissipates most power for a wide frequency range. This simulation results is consistent with the theoretical analysis from the previous section, i.e. the R_0=2R gives the best power attenuation condition to the backward wave in RTWO. Since backward wave is primarily from disturbance, it has broad band nature and can be best attenuated under the above condition.

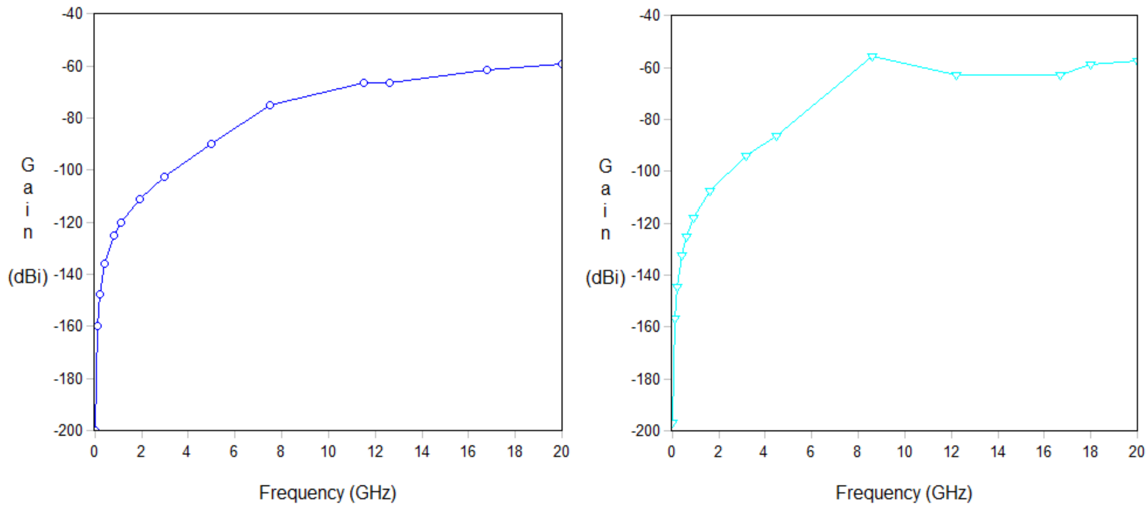

Fig. 5. (a) Farfield for R=25 ohms ; (b) Farfield for R=Infinite.

4. Conclusion

We presented nonlinear analysis and EM simulation of RTWO with primary focus on backward wave attenuation. The impact of backward waves on the RTWO's performance is clarified and optimal on-resistance for backward wave attenuation has been proposed. We have established that to obtain a good performance measure in terms of phase noise, one need to pay attention to the value of this shunt resistance which provides guidance for the design of the cross-coupled inverter pair of RTWO.

References

[1] John Wood, Terry C. Edwards, Steve Lipa, "Rotary Travelling Wave Oscillator Arrays: - A New Clock Technology," IEEE J. Solid-State Circuits, vol. 36, no. 11, pp. 1654 – 1665, Nov. 2001.

[2] G. Le Grand de Mercey, "An 18 GHz Rotary Traveling Wave VCO in CMOS with I/Q Outputs," in IEEE Solid-State Circuits Conf., Sept. 2003, pp. 489 – 492.

[3] William Andress and Donhee Ham, "Recent Developments in Standing-Wave Oscillator Design: Review," in IEEE Radio frequency and Integrated Circuits Symp., Jun. 2004, pp. 119 - 122.

[4] Hsieh-Hung Hsieh, Ying-Chih Hsu, Liang-Hung Lu, "A 15/30 Dual-band Multiphase Voltage Controlled Oscillator in 0.18-um CMOS," IEEE Trans. Microwave Theory and Techniques, vol. 55, no. 3, pp. 474 – 483, Mar. 2007.

[5] Takinami K., Walsworth R., Osman S., Beccue S., "Phase-Noise Analysis of Rotary Travelling-Wave Oscillators Using Simple Physical Model," IEEE Trans. Microwave Theory and Techniques, vol. 58, no. 6, pp. 1465 – 1474, May 2010.

[6] Cheng Zhuo, Huafeng Zhang, Samanta, Rupak Samanta, Jiang Hu, Kangsheng Chen, "Modelling, Optimization and Control of Rotary Travelling-Wave Oscillator," in IEEE/ACM Int. Computer-Aided Design Conf., Nov. 2007, pp. 476 – 480.