Design of a 85 GHz Rotary Traveling Wave Oscillator for Imaging Applications

Samar Hussein
Electronics and Communication Department
Faculty of Engineering, Ain Shams University
Cairo, Egypt
samar.abdelnasser@eng.asu.edu.eg

Ahmed Eladawy
Electronics and Communication Department
Faculty of Engineering, Cairo University
Cairo, Egypt
aeladawy74@gmail.com

***Abstract*—**This paper presents the design of a Rotary Traveling Wave Oscillator (RTWO) at 85GHz. The oscillator can be useful in imaging applications. It is implemented in 65nm commercial CMOS technology. The total area of the oscillator is 0.185x0.185 mm^2. The total power consumption is 25 mA out of 1.5 V supply.

Keywords-*Rotary Traveling Wave Oscillator, Imaging Applications, Distributed Oscillators*

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I. INTRODUCTION

Imaging applications need high-frequency sources with reasonable power consumption levels while maintaining low cost and compact size. This has been a challenge to achieve in the past few years using the traditional LC-lumped based oscillators. As the frequency ranges keep increasing, the realization of small enough integrated reactive components has become much harder and not even realizable as the frequency demand approaches hundreds of GHz. As a result, the concept of using transmission lines in oscillators has emerged. These oscillators can provide different oscillation phases by tapping different points along its length. Moreover, they can provide high-resolution oscillation phases at reasonable power consumption compared to LC- lumped base counterparts.

The miniaturization of metal-oxide-semiconductor (CMOS) technology has enabled the competition with other technologies such as SiGe, GaAs and bi-polar on cost and power consumption scale; which makes CMOS technology the best to provide fast time-to-market and low cost products with high level of integration.Besides, CMOS offers the ability to implement strip-line on chip given that the distance between the top thick metal layer and the substrate is sufficiently large. This is an advantage for high speed applications despite the low resistivity of the substrate [1] [2]. New architectures of high speed oscillators have been adopted by monolithic transmission line on CMOS chips like rotary traveling wave oscillator (RTWO) which will be discussed in the following sections.

In this work, the design of a fully differential RTWO at 85GHz will be presented. The concept of distributed amplifiers/oscillators is shown in section II. The model of transmission lines used in the distributed amplifiers/oscillator will be discussed in section III. The structure of the designed RTWO is presented in section IV and finally layout considerations and simulation results are shown in section V. Finally, conclusions are provided in section VI.

II. DISTRIBUTED AMPLIFIERS/OSCILLATORS

The concept of distributed amplifiers has first been introduced in 1936 by W. S. Percival of the UnitedKingdom. Many publications have been developed about that concept as in [3] and [4]. Now, distributed amplifiers are known for their use in wideband applications. The advantages of distributed amplifiers compared to traditional ones will he highlighted.

Gain-Bandwidth product is considered a figure of merit for traditional active components based amplifiers and it should remain constant for certain technology regardless of the topology of the amplifier. This has been a challenge for the demand of high gain- high bandwidth applications given the fact that there is always trade-off between the amplifier's gain and bandwidth. The gain bandwidth product depends on the trans-conductance and load capacitance of the transistor, so there is no way to have higher bandwidth without degrading the gain. Using cascaded amplifiers helps increasing the gain-bandwidth product but not when the gain approaches unity. On the other hand, the distributed amplifiers have a gain-delay trade-off instead of gain-bandwidth in case of traditional amplifiers which is a huge advantage of such amplifiers. This feature makes them very suitable for high bandwidth applications.

Distributed amplifier consists of two parallel transmission lines; separated by distributed active components along their lengths and by transistors in the simplest case. One transmission line is connected to the gates of the transistors while the other line is connected to the drains of the same group of transistors. The end of each transmission line is connected to bias resistor R_{bias} for dc coupling. The bias resistors should be equal to the characteristic impedance of the transmission line in order to avoid any unwanted reflections that could affect the amplification reliability. The model of this distributed amplifier is shown in Fig.1. The way it works is as follows: when an input signal is applied to the gate of the first transistor in the group, the output at the drain is amplified. Both gate and drain signals of the first transistor propagate through their transmission lines respectively. This is repeated at each transistor along the length of the transmission lines. In order to have the drain signals from successive transistors added constructively to each other, the delay between two successive transistors' gates should equal the delay between their corresponding drains ($\tau_g = \tau_d$) as illustrated in Fig. 1.

The overall gain depends on the number of transistors only since the gain of each transistor is independent of the other ones as opposed to cascaded traditional amplifiers. This is true regardless of the specific gain of each transistor; in other words the overall gain will persist to be high even if any transistor gain approached unity. The bandwidth of distributed amplifier is determined by the equivalent network of the transmission lines and parasitic capacitances of each transistor (Cgs and C_{ds}) . The bandwidth of the transmission lines is determined by its total capacitance and inductance which equal its equivalent lumped capacitance and inductance. The input and output capacitance of the transistor providing the gain are absorbed in the transmission line.

After introducing the concept of distributed amplifiers, it is the time to expand this concept to oscillators as well. An oscillator is nothing but an amplifier with positive feedback as shown in Fig. 2.

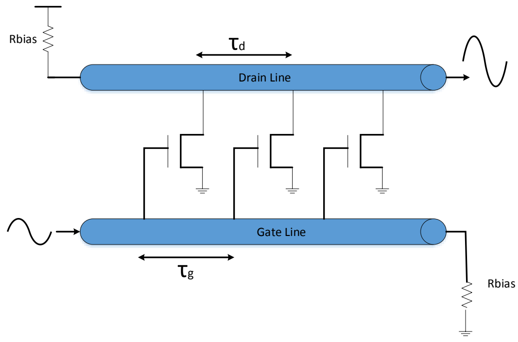

Figure 1. Distributed Amplifier

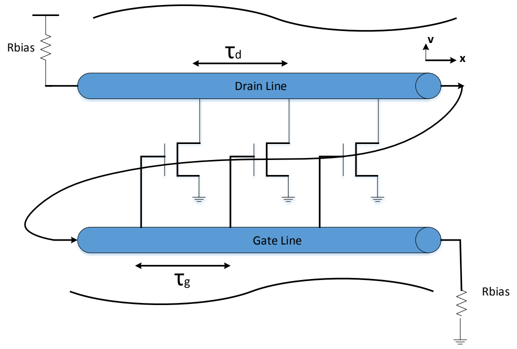

Figure 2. Distributed Oscillator

III. TRANSMISSION LINE MODEL

The properties of transmission line like characteristic impedance Z_0, propagation constant β, attenuation constant α etc. can be obtained from the solution of the well-known telegrapher's equations [5].Telegrapher's equations in the frequency domain are as follows:

$$\frac{dV(z)}{dz} = -(R + L\omega)I(z) \quad (1)$$

$$\frac{dI(z)}{dz} = -(G + C\omega)V(z) \quad (2)$$

Where L, C, R, G are the circuit parameters per unit length Combining these two equations and solving the resultant wave equations gives the following:

$$V(z) = V_o^+ e^{-\gamma z} + V_o^- e^{\gamma z} \quad (3)$$

$$I(z) = \frac{1}{Z_o}(V_o^+ e^{-\gamma z} + V_o^- e^{\gamma z}) \quad (4)$$

Where

$$\gamma = \alpha + j\beta = \sqrt{(R + jL\omega)(G + jC\omega)} \quad (5)$$

Is the propagation constant and

$$Z_o = \sqrt{\frac{R+jL\omega}{G+jC\omega}} (6)$$

Is the line characteristic impedance

A. *Untapped Transmission Line*

Assuming low-loss transmission line where $(R \ll \omega L \text{ and } G \ll \omega C)$

In this case attenuation constant, phase constant, phase velocity and characteristic impedance respectively are given as follows [5]:

$$\alpha \approx \frac{1}{2}(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}}) \quad (7)$$

$$\beta \approx \omega\sqrt{LC} \ (8)$$

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} (9)$$

$$Z_o \approx \sqrt{\frac{L}{C}} \quad (10)$$

B. *Tapped Transmission Line*

We can use those equations to obtain a tapped transmission line properties compared to the untapped one. A model of periodically loaded transmission line is shown in Fig. 3.

Assuming that C_{load} is loading the transmission line regularly each l distance on the strip line, it means that C_{load} is equivalent to a uniformly distributed capacitance along the length of the transmission line. Consequently, the line characteristic impedance can be rewritten as follows:

$$Z_o = \sqrt{\frac{L}{C + C_{load}\ /l}} \quad (11)$$

And the propagation constant assuming low-loss or lossless line can be rewritten as follows:

$$\beta = \omega\sqrt{L(C + \frac{C_{load}}{l})} \quad (12)$$

The loading distributed capacitance increases the propagation constant and decreases the characteristic impedance.

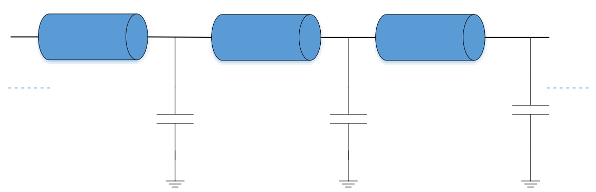

Figure 3. Periodically loaded Transmission Line

IV. RTWO STRUCTURE

The RTWO is based on distributed resonator principle. It consists of differential strip-line integrated on the top metal layer of the used technology and is loaded with gain stages distributed along its length to provide enough gain for sustained oscillations. Traveling wave oscillators provide different phases by tapping along different points along their length in a power efficient way and less complex circuitry compared to traditional LC oscillators [6]. This is especially useful at higher frequencies close to the cutoff frequency of a technology active elements. The design flow of a differential RTWO within a frequency range suitable for imaging applications; specifically skin cancer detector; is the main focus of the proposed work.The simulation of the RTWO is carried out using EMX (electromagnetic simulator) and Cadence.

In order to extract the equivalent model of the used transmission line, EMX is used; which performs electromagnetic analysis on the gds of the transmission line across the desired frequency range. EMX assumes low-loss transmission line model and series RLC circuit model when solving any transmission line structure. It generates s-parameters file which can be used in n-port model in cadence and can be integrated with transistor level circuits. Moreover, EMX can generate some important parameters of a transmission line such as propagation constant β, attenuation constant α and characteristic impedance Z_o. Using those parameters, the transmission line circuit model parameters can be calculated.

The extracted quarter transmission line parameters vs. solution frequency are shown in Fig. 4. The equivalent circuit parameters of one quarter of RTWO structure at 85GHz (desired oscillation frequency) are shown in Table. 1.

TABLE I. QUARTER TRANSMISSION LINE EXTRACTED PARAMETERS AT 85GHZ

Parameter	Extracted Value	Unit
Real Charactristic Impedance Z_0	42.88	Ω
Propagation Constant β	1034	Rad/m
Attenuation Constant α	21.9	Np/m
Total Capacitance C	45	pF
Total Inducatance L	82	nH
Total Resistance R	938	Ω

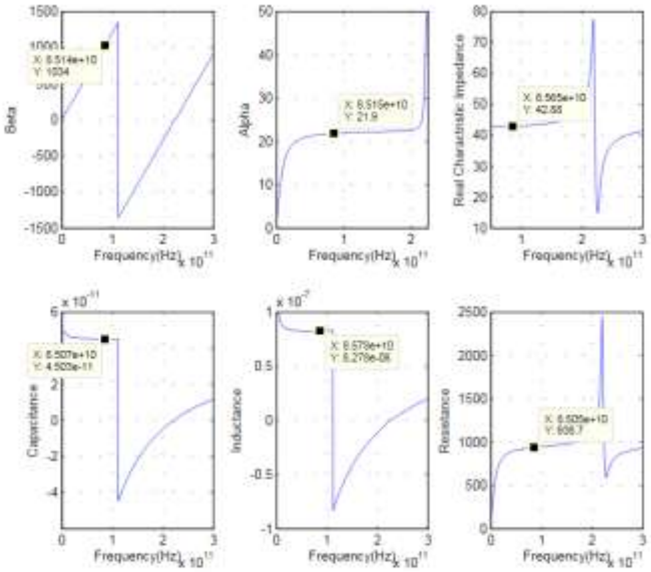

Figure 4. Extracted TL Parameters vs. Frequency

The oscillator consists of four identical quarters; providing four phases (0^0, 90^o, 180^o, 270^o) as shown in Fig. 5 where each quarter consists of two identical transmission lines. Cross-coupled gm stages are used per quarter to provide each enough gain to overcome the transmission line resistive losses. The symmetry of the four quarters (including transmission lines lengths and gm stages distribution) is crucial to maintain the balance of the four phases. The travelling mode direction is rather forced by adjusting input and output tapping points of the cross-coupled gm stage.

Cross-coupled nmos pair was used as the source of the negative resistance. They are loaded with diode connected pmos transistors. The pair is biased through its drain; gate and drain are shorted together on the transmission line level. Nmos gate and drain are placed at different points on the transmission line to favor one traveling direction over the other. The gain stage acts like a shunt conductance parallel with oscillator conductance (resistive losses).

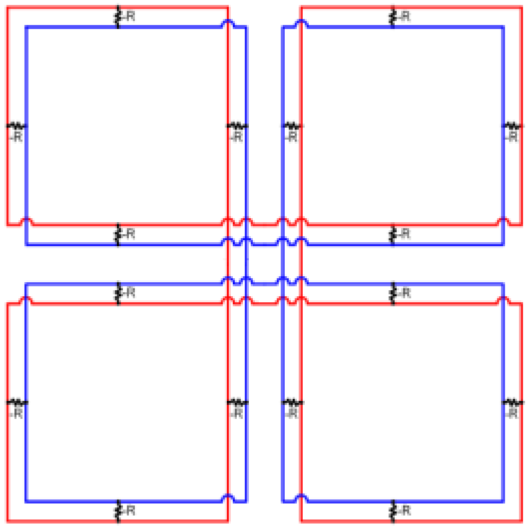

Figure 5. RTWO Structure

V. LAYOUT CONSIDERATIONS AND SIMULATION RESULTS

A. *Layout Considerations*

The differential transmission lines are implemented on M7 to minimize the resistive losses. Transmission lines dimensions are chosen to resonate at 85 GHz. Each loop is 292 um length and 6 um wide. The spacing between both lines is 3 um.

B. *Simulation Results*

The extracted s-parameters of the oscillator transmission lines layout are used in the simulation to evaluate the total loss at the desired frequency in order to estimate the required gm to compensate for this loss and make the oscillation starts. The total trans-conductance of the oscillator structure and the cross-coupled gm stages is shown in Fig. 6. The four oscillation phases are shown in Fig. 7.

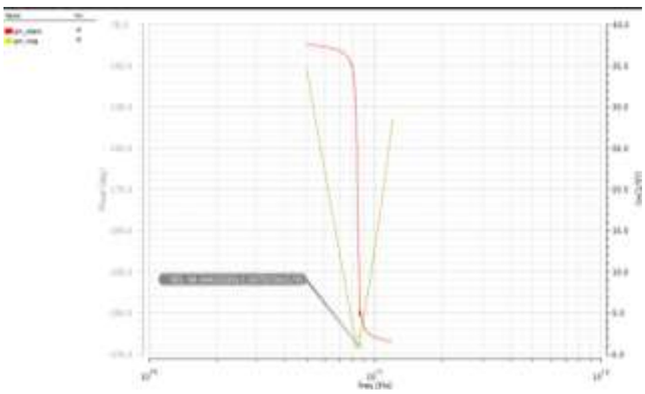

Figure 6. Total Conductance of RTWO

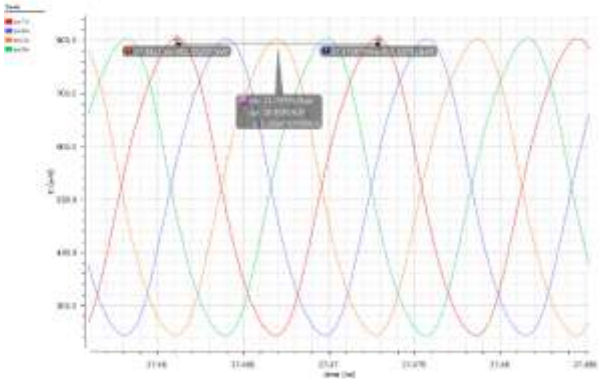

Figure 7. The four phases of RTWO

VI. CONCLUSIONS

A Rotary Traveling Wave Oscillator (RTWO) with fundamental frequency of 85GHz provides four quadrature phases (0^o, 90^o, 180^o, 270^o) with 1V pp swing. Total power consumption is 25 mA.

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