Zero Delay Clocking System in GHz Frequency Regime using CRLH Metamaterial Structure

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***Abstract*—In a multilayer structure of Integrated Circuit (IC) chips, clock signals are distributed through intermediate/global interconnects of clock tree network. These metal lines are very thin and offer high resistance and capacitive loading to the propagating electrical signals resulting in interconnect delay. This has significant impact on the propagation of clock signals, especially in GHz regime. In this work, we propose a Composite Right/Left Handed (CRLH) system augmenting the long metal interconnect line to reduce/remove the delay in the propagation of the clock signals. The CRLH system is shown to have minimum signal reflection at its resonant frequency and this feature is used for the transmission of high speed clock signals. We have designed a CRLH structure to resonate at 10 GHz. Simulation results show that when the clock signals are transmitted through interconnect-CRLH-interconnect system at this frequency, the propagation delay reduces almost to zero.**

I. Introduction

In high speed application ICs, data, control and other associated signals are driven by clocks at Giga Hertz (GHz) frequencies [1]. Clock signals communicate with other on-chip blocks through interconnects and these lines offer high resistance for the propagation of the signals [2]. Due to this, signal deteriorating effects like delay, skew, jitter etc. add to the propagating signals and clock signals are no exception to this phenomena. These effects are predominant in GHz frequencies and limit the maximum speed and efficiency of the IC chips [3]. Hence, there is a need to remove/reduce the delay in the propagation of the clock signals through the metal interconnects in high frequency applications to improve the performance of the ICs. In this paper, we present a method to reduce the delay in clock signals using a resonating network that employs metametrial structures.

Electromagnetic metamaterials are defined as artificial homogeneous electromagnetic structures with unusual properties, not readily available in nature. Metamaterials exhibit backward-wave propagation over a specific frequency range, which is determined by their geometry and material characteristics. The idea of negative permeability (μ) and permittivity (ε) was originally introduced in [4]. In his paper [4], Veselago speculated on the possible existence of Left Handed Materials (LHM) and anticipated their unique electromagnetic properties such as the reversal of Snells Law and Doppler effect.

The first Left Hand (LH) prototype was built with thin wires called split-ring-resonators which is inherently lossy and narrow-band [5]. Transmission Line (TL) metamaterials are proposed to improve the loss and bandwidth characteristics [6]. A TL metamaterial is constructed by creating a high-pass transmission line i.e. loading a common TL with series capacitances and shunt inductances [7]. Properly choosing the values of the inductive (L) and capacitive (C) loading components, it is found that particular TL exhibits negative μ and ε and such a structure is termed as Composite Right/Left Handed (CRLH) metamaterial.

CRLH structures find their use in various microwave applications ([8], [9]). Various types of delay lines constructed using CRLH structures are used in signal processing applications, radar and phased array systems ([10], [11], [12]). In [13], CRLH structure is cascaded with Radio Frequency (RF) power amplifier circuit to reduce the group delay of the circuit. The RF power amplifier circuit is made to operate in the frequency range in which the CRLH structure has negative group delay.

In all the above literatures, CRLH structures are used as devices and as tunable delay lines in microwave applications. However in microwave applications, delay in clock signal when transmitted through metal interconnects is an important issue because at such high frequencies, even a delay (parasitic) of a few pico seconds is detrimental to the proper functioning of the circuit. The CRLH transmission line has a unique feature of supporting an infinite wavelength wave at a nonzero frequency. In this paper, we use this property to show that the delay in the propagation of clock signals in a long interconnect can be considerebly reduced by augmenting it with a CRLH structure

The rest of this paper is organized as follows. A Transmission Line based CRLH structure and the theory behind its left and right handed behaviour is given in section II. Simulation results showing delay reduction in high speed clock signals employing CRLH system is shown in section III. The conclusions are given in section IV.

II. CRLH TL Theory

The CRLH structure is implemented using microstrip transmission lines as shown in figure 1 [14]. The set of microstrips form the inter digital capacitor and the two ends of the structure is connected to the ground plane through vias and form a stub, which is electrically equivalent to an inductor.

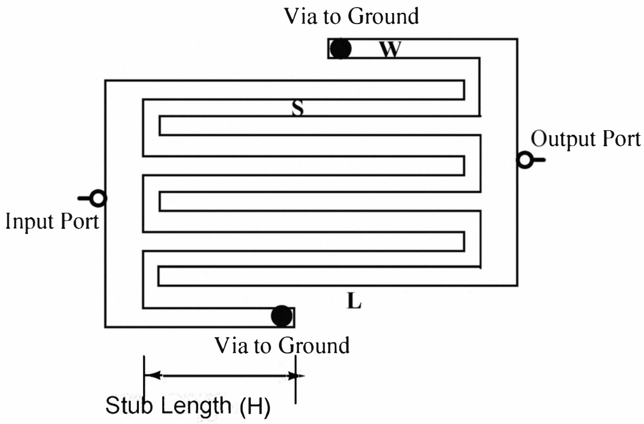

Fig. 1. CRLH structure using microstrip lines

The general model of a single cell lossless CRLH TL is shown in figure 2. In figure 2, L'_R, C'_L, C'_R and L'_L indicates the right handed inductance, left handed capacitance, right handed capacitance and left handed inductance (all values are per unit length) respectively.

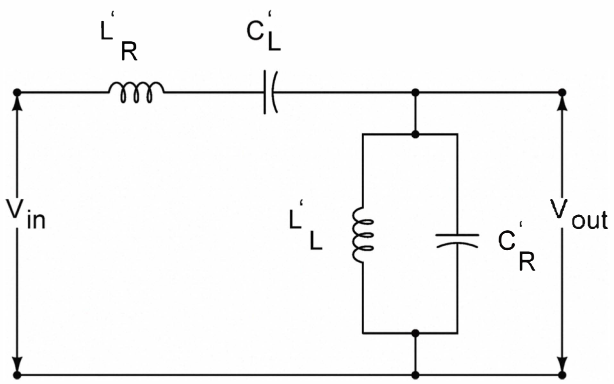

Fig. 2. Equivalent circuit model of CRLH TL

The contributions C'_L and L'_L are provided by the inter digital capacitors and stub inductors whereas the contributions C'_R and L'_R come from their parasitic effects and has an increasing effect with increase in frequencies. The parasitic inductance L'_R is due to the magnetic flux generated by the currents flowing along the digits of the capacitor and the parasitic capacitance C'_R is due to the parallel plate voltage gradients existing between the trace and the ground plane. Thus the circuit given in 2 is equivalent to the structure shown in figure 1. The complex propagation constant (γ) of the CRLH TL cell is given as [7]

$$\gamma = \alpha + j\beta = \sqrt{Z'Y'} \tag{1}$$

where α and β denotes the attenuation and propagation constant of the CRLH TL. Per-unit-length impedance (Z') and admittance (Y') are defined as (obtained from figure 2)

$$Z' = j(\omega L'_R - \frac{1}{\omega C'_L}) \tag{2}$$

$$Y' = j(\omega C'_R - \frac{1}{\omega L'_L}) \tag{3}$$

Expression for β is obtained from equations (2) and (3) and given as

$$\beta = (\frac{\omega}{\omega'_R} - \frac{\omega'_L}{\omega}) \tag{4}$$

where $\omega'_R = \frac{1}{\sqrt{L'_R C'_R}}$ and $\omega'_L = \frac{1}{\sqrt{L'_L C'_L}}$.

In equation (4), first term represents a linear phase related to the right handed contribution and the second term corresponds to the left handed contribution. The dispersion plot of Omega (ω) versus Beta (β) is obtained using equations (2), (3) and (4). Figure 3 shows dispersion plot comparison of balanced CRLH structure with that of Pure Left Hand (PLH) and Pure Right Hand (PRH) materials [15].

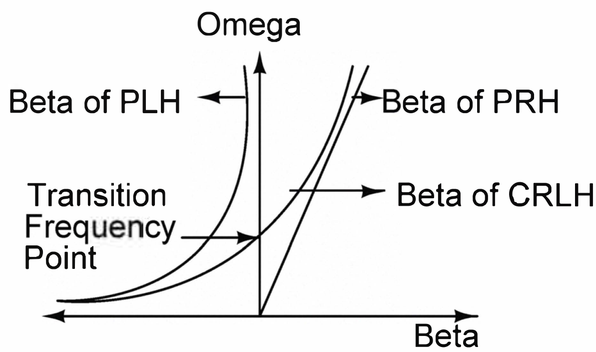

Fig. 3. Dispersion of CRLH compared with PLH and PRH materials

The transition frequency point (ω_0 in figure 3) of the CRLH structure is obtained by making $\beta = 0$ in equation (4) and is given as

$$\omega_0 = \frac{1}{\sqrt[4]{L'_R C'_R L'_L C'_L}} \tag{5}$$

In equation (5), at ω_0, guided wavelength (λ_g) becomes ∞ and this is the condition for Zero Order Resonance (ZOR). The parameter λ_g is defined as c/f where c is the speed of light in free space and f is the signal frequency. The resonant frequency depends on the shunt LC tank circuit and is given in equation (6). Hence ZOR frequency does not depend on the physical length of the resonator.

$$\omega_{ZOR} = \frac{1}{\sqrt{L'_L C'_R}} \tag{6}$$

At the transition frequency ($L'_R C'_L = C'_R L'_L$), phase ($\Delta\phi_C(\omega = \omega_0)$) is 0 which indicates at $\omega = \omega_0$, phase is at the origin of the CRLH structure.

III. Simulation Results

A. Simulation of CRLH Structure

CRLH system to transmit clock signal with minimum delay is shown in figure 4. The CRLH structure is simulated with dielectric thickness of 39 μm, relative permittivity (ε_r) of 2.5 and conductor thickness of 1.5 μm. The dimensions of the structure is optimized for the the ZOR at 10 GHz using Agilent ADS. The corresponding dimensions of the CRLH structure are given in Table I.

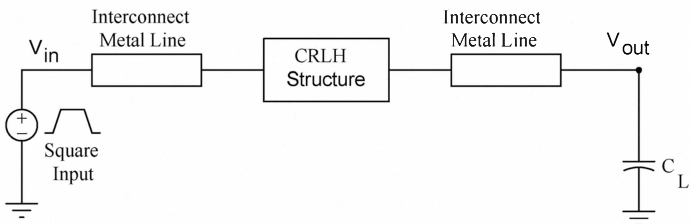

Fig. 4. System used to transmit clock signal with minimum delay

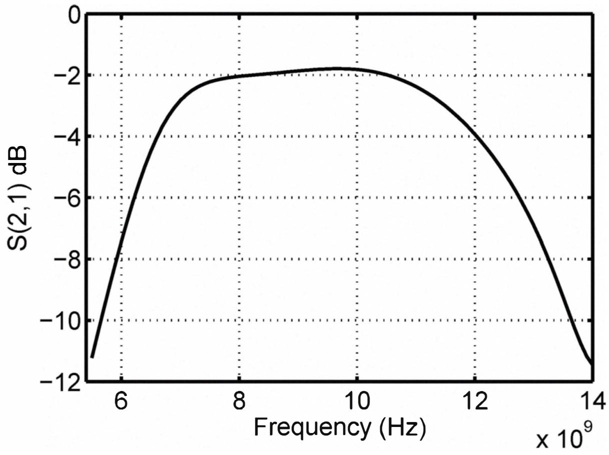

Fig. 5. Transmission characteristic of the CRLH structure

TABLE I
DIMENSIONS OF THE CRLH SYSTEM

Structure	Dimensions	Unit
Finger length (L)	250	μm
Metal interconnect length	250	μm
Finger width (W)	8	μm
Length of the stub (H)	190	μm
Via diameter	6.4	μm
Number of fingers	3	-
Load capacitance (C_L)	100	fF

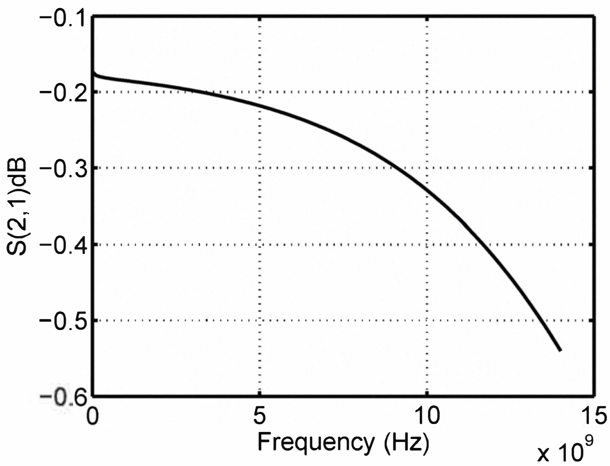

Fig. 6. Transmission characteristic of the TL

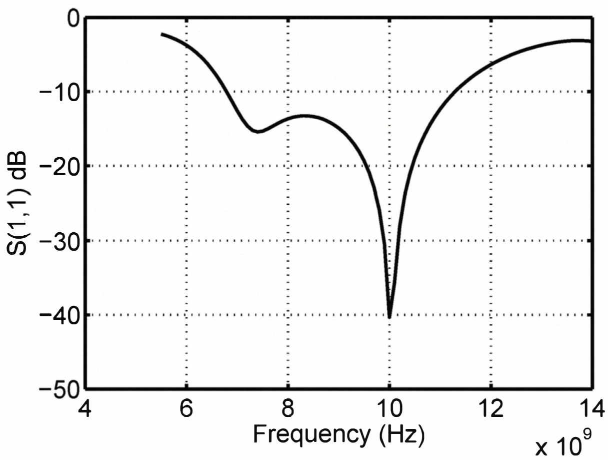

Fig. 7. Signal reflection at the input side

S parameter analysis is made to study the behavior of the CRLH structure and compared with the characteristic of the transmission line (termed as RH TL) structure. In the simulation, receiver part is modeled as load capacitance (C_L). The transmission characteristic plot (S(2,1) in dB) of the CRLH structure is shown in Fig. 5 and is similar to that of a band pass filter response. At low frequencies, CRLH TL behaves like a PLH TL and at high frequencies, the structure behaves like a PRH TL. At all other frequencies, the transmission characteristics depend on the combination of LH and RH contributions. Whereas, characteristic plot of a TL is similar to that of low pass filter and is shown in figure 6. Figure 7 shows the reflection response (S(1,1) in dB) at the input side of the CRLH system and shows that reflection is minimum at 10 GHz.

To find the transition frqeuncy of the CRLH structure, dispersion curve (f versus β) is plotted as shown in figure 8. The propagation constant (β) is obtained from transmission parameter (S(2,1)) of the CRLH TL as

$$\beta = -\varphi^{unwrap} * S(2,1) \quad (7)$$

Phase of S(2,1) is a curve varying between $-\pi$ and $+\pi$ whereas the dispersion characteristic β is a continuous function of frequency. Hence the phase of S(2,1) is unwrapped in order to restore the continuous nature of β. In the dispersion plot shown in figure 8, phase is at the origin at 10 GHz. Hence this is the ZOR frequency of the designed CRLH system. Whereas the dispersion plot of the transmission line is positive linear as shown in figure 9.

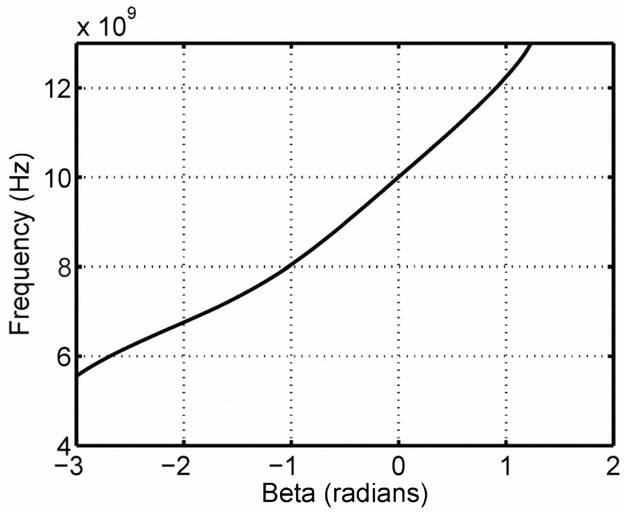

Fig. 8. Dispersion plot of the CRLH stricture

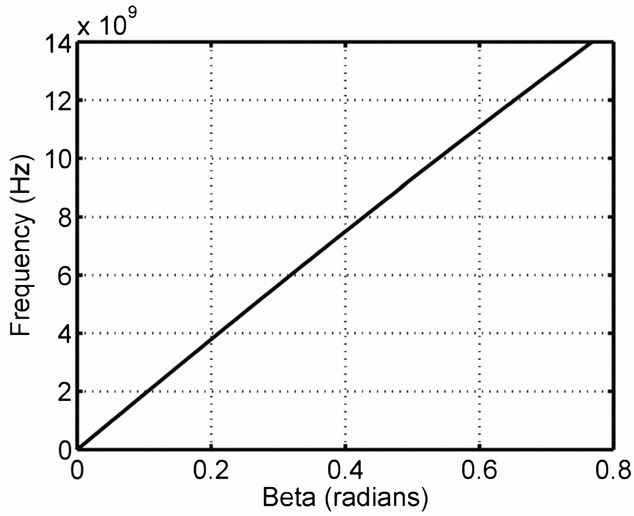

Fig. 9. Dispersion plot of the transmission line

B. Simulation of Interconnect-CRLH-Interconnect System

The CRLH system shown in figure 1 has a resonant frequency of 10 GHz. Hence the transmitted signal at 10 GHz through the structure has minimum propagation delay. Figure 10 shows the input clock signal and the the transient responses of a transmission line (representing an interconnect line) with and without the CRLH stucture. When the circuit in figure 4 is excited with a square wave signal (clock signal) (period as 100 psec with rise time as 10 psec), the output is in phase with the input signal as shown in figure 10. The responses clearly show that the signal is delayed considerably when propagated through the transmission line without a CRLH stucture.

The overall size of the CRLH cell is in hundreds of microns even for a resonant frequency of 10 GHz. If the source node (example : buffer output) and the load node (example: input of a flip flop) of a clock network have distances less than a few tens of microns, CRLH structure will not be a good choice. In such short range clock distribution networks, metal interconnects are preferred over CRLH structures.

For system having a regularly spaced clock load such as pipeline stages, clock skew can result in data hazards. To model the efficiency of the CRLH structure for such applications, we have considered a regularly spaced series and parallel distributed load as shown in figures 11 and 12.

Simulations are carried out to see the effect of variations in the load capacitance (C_L) and the interconnect length (T_L) for the two models (Figures 11 and 12). Results in both the cases are almost identical and it is observed that the clock signal is not affected as long as the interconnect length and the load capacitance values are within certain bounds. Table II and III shows the upper bounds for the length and the load capacitance values for different number of sections of metal interconnect and load. If the length of the interconnect is increased beyond the upper bound, the amplitude of the clock signal increases whereas if the load capacitance is increased beyond the upper bound, the clock signal attenuates. For the typical values of C_L (=50 fF) and T_L (=125 μm), it is found that the propagated clock signal gets attenuated for both models as the number of sections increase.

TABLE II
MAXIMUM UPPER BOUND OF THE T_L AND C_L FOR DIFFERENT NUMBER OF SECTIONS IN CASE OF MODEL 1

Number of Sections	Maximum T_L (μm) when C_L= 50 fF	Maximum C_L (fF) when T_L= 125 μm
1	600	165
2	220	95
3	120	65
4	100	55

TABLE III
MAXIMUM UPPER BOUND OF THE T_L AND C_L FOR DIFFERENT NUMBER OF SECTIONS IN THE LOWER BRANCH IN CASE OF MODEL 2

Number of Sections	Maximum T_L (μm) when C_L= 50 fF	Maximum C_L (fF) when T_L= 125 μm
1	600	80
2	200	55
3	100	38

IV. CONCLUSIONS

In this work, we have shown that the delay in the transmission of clock signals over long interconnects can be reduced by augmenting a CRLH metamaterial structure with the interconnect line. The designed CRLH structure is found to resonate at a frequency of 10 GHz and offer zero delay to the clock signals when operated at its resonant frequency. A comparison of transmission and dispersion characteristic of CRLH and transmission line is made. It is found that the delay in the clock signal is not affected as long as the interconnect length and the load capacitance values are within certain bounds.

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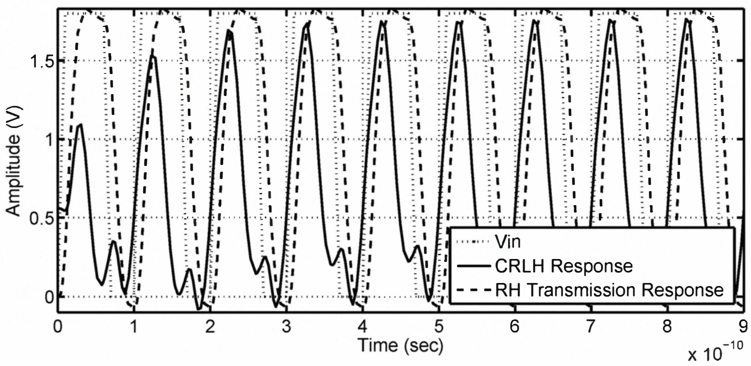

Fig. 10. Comparison of the delay in the transmission of the clock signal through the CRLH and transmission line

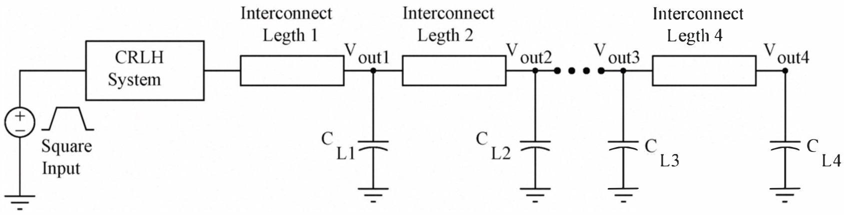

Fig. 11. Model 1

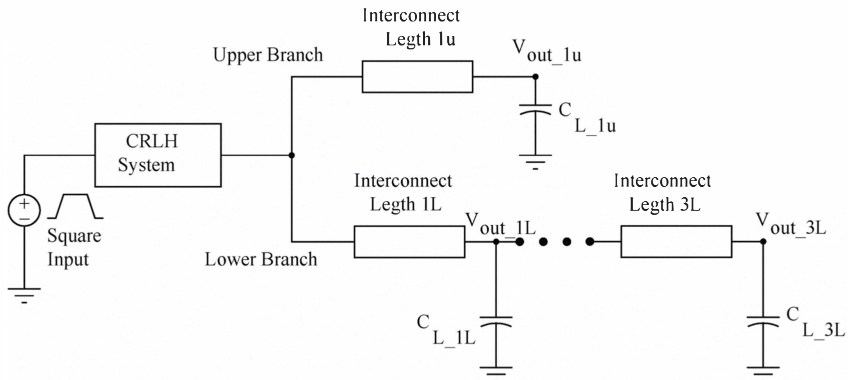

Fig. 12. Model 2

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