DNA Logic Gates to Design Half Adder

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Abstract

The DNA molecule is indubitably the most powerful medium known for data storage and processing. But till now, DNA molecule has found little use in computing applications. For initiating computing application with DNA molecule, it requires to design DNA transistors which can be utilized to design basic gates to implement Boolean logic. Interestingly some recent researches have shown that it is very much possible to design a three terminal transistor like device architecture by controlling the flow of RNA polymerase along DNA with specific integrases. Along with that, very recently, fundamental experimental designs for realizing various basic Boolean logic functions have been demonstrated successfully with DNA molecule. Present work adopted, modified and extended such DNA logic gate concept to execute design simulation of a half adder circuit. The timing diagram for sum, carry, input and output has been simulated and results have been presented. With present research, it has been established that such DNA logic gate concept can be extended to complex circuits. At the same time, it has been also predicted that with the development of proper mathematical model for DNA transistor, a circuit simulator can be designed for designing and simulating bioelectronics circuit in near future.

Keywords: *DNA, RNA, transistors, logic gates, simulation*

INTRODUCTION

The world of electronics starts with a material called “semiconductor” which can be induced to conduct or stop the flow of electrons or holes. During last sixty years, the silicon has been the most popular semiconductor material used to make chips and the basic working unit on a chip is the transistors. In conventional electronic circuits transistors are implemented to process, store and transfer signal or data with the flow of electrons or holes. Where as two or more transistors together form a logic gate, which allows a computer to manage mathematical operations. From the beginning to till date, the main aim of the electronics industry is to produce more powerful chips. In that process, designers have shrunk transistors in size to produce smaller, faster, power efficient chip at lower price [1]. The net result of this transistor scaling action is the concentrated intense electrical activities in a diminishing space. So far that has produced small, faster, cheaper chips but at a certain point, heat and other forms of interference could disrupt the inner workings of silicon chips [1]. As a result, scientists and technologists are looking for new materials, innovative structures and revolutionary ideas to realize reliable transistor like action in such tiny space [2].

Presently throughout the world several groups of scientists, researches and technologists are trying to store, retrieve and process signals using bio-chemical reactions with newer biological materials [3–5]. In such context, with research it has been proven that, the blueprint for life DNA, can also become the templates for making a new generation of transistors, logic gates and subsequent computer chips [6]. In last decades lots of research articles have been reported on experimental realization of transistor like action and logic operation with DNAs [7–9]. Recently, Drew Endy *et al.* at Stanford University in California have designed a transistor like device that controls the movement of an enzyme called RNA polymerase along a strand of DNA with bacteriophage serine integrases [10]. They have also experimentally created logic gates that allow both information storage and logical operations with multiple transcriptors [10]. Such remarkable break through can be utilized to realize biochip and subsequent biological computers which can be used to study and reprogram living systems, monitor environments and improve cellular therapeutics [9–10]. Till now most of the research activities related to DNA logic gate realization are concentrated into intense experimental activities. But, along with such experimental ventures theoretical simulation is also important to understand the operation and functionality of higher order circuits with such DNA based logic gates. Under the present work, based on DNA logic gates, a half adder has been logically realized with MATLAB Simulink.

The sum and carry for the DNA half adder has been simulated and verified with timing diagrams. Such simulation work will not only justify the applicability of such DNA logic gates in complex circuit realization, it will also lead a step forward towards practical implementation of Bio-computers. Same time extension of present research with the development of proper mathematical model of DNA transistor will initiate the development of circuit simulator with DNA logic gates.

LOGICAL MODELING

The RNA polymerase is an enzyme that produces RNA chains using DNA genes as templates, a process called transcription [11].

The RNA synthesis follows after the attachment of RNA polymerase to a specific site, "promoter", on the template DNA strand and the synthesis process continues until a termination sequence ("terminator") is reached [12]. This process of producing primary transcript RNA can be reconfigured with a transistor like three terminal device model which can be named as transcriptor [10].

The flow of RNA polymerase along DNA strands between input and output will be defined as transcriptional current. The gate like control will be realized with independent chemical control signals (defined as "integrase") which will regulate the flow of RNA polymerase to realize Boolean logic operation (Figure 1) [10].

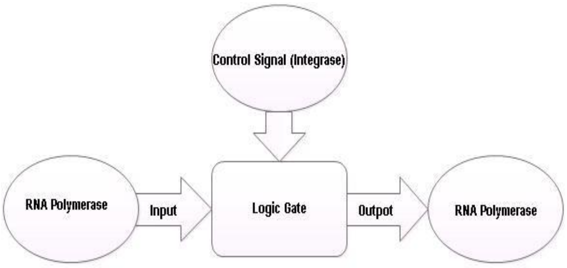

Fig. 1: *Schematic for Equivalent Logic Representation.*

As shown in the Figure 2, the logic element will use asymmetric transcription terminators as reversible check valves. A transcription terminator will be accommodating two opposing DNA recombination sites named as Transcription Elements (TEs, represented with dark green and dark blue solid triangles) which will normally disrupt RNA polymerase flow. The input integrase which is recombinases (genetic recombination enzymes) will catalyze unidirectional inversion of DNA within opposing recombination sites [10]. This will modify TEs (represented with partially dark green-blue and partially dark blue-green solid triangles) and invert of the transcription terminator to provide of DNA recombination sites and will resultant RNA polymerase flow. Every opposing recombination sites (TEs) will be recognized by independent integrases which will provide independent control over the orientation or presence of one or more terminators.

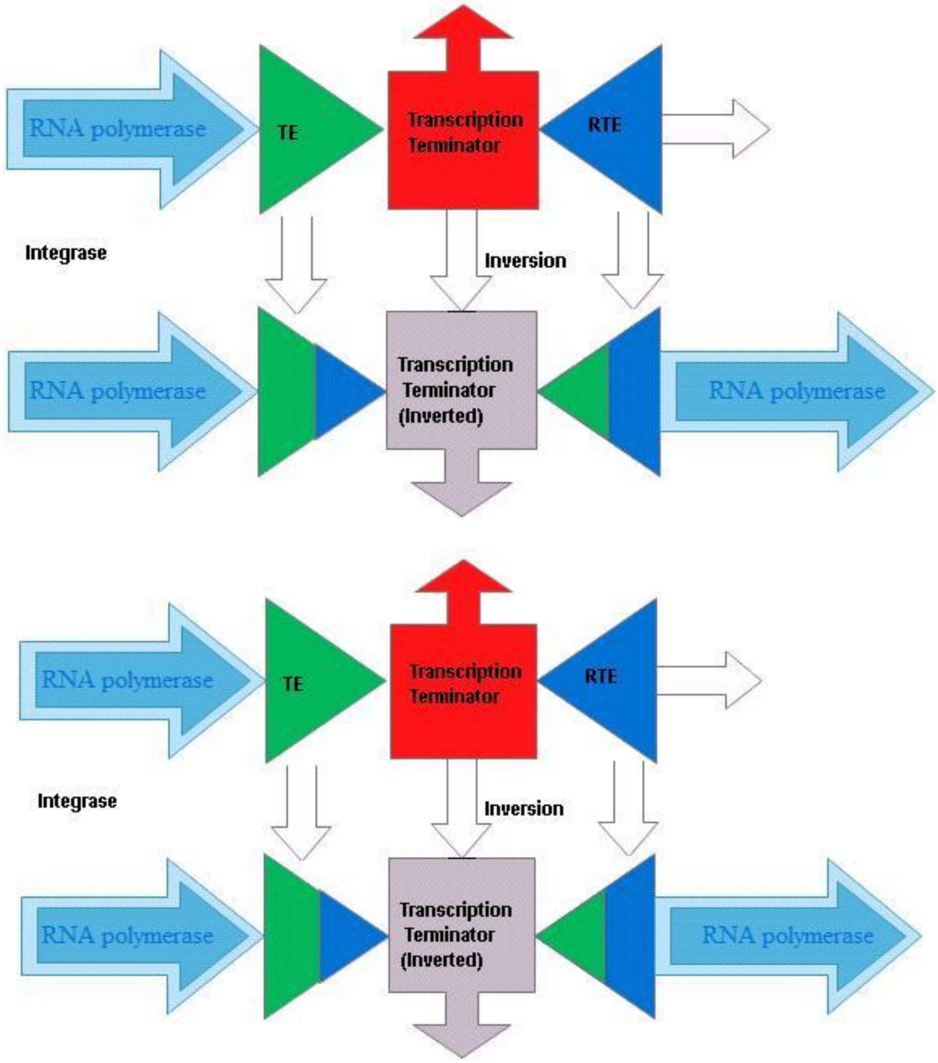

Fig. 2: *Logic Control of RNA Polymerase Flow with Integrase.*

Symbols: TE: Transcription Elements, RTE: Recombination sites for TE. Under the present work, "half adder", a functional digital circuit built with two logic gates (one EXOR and one AND), has been designed. The half adder adds two one-bit binary numbers and the outputs will be produced as the sum of the two bits and the carry as shown in Figure 3.

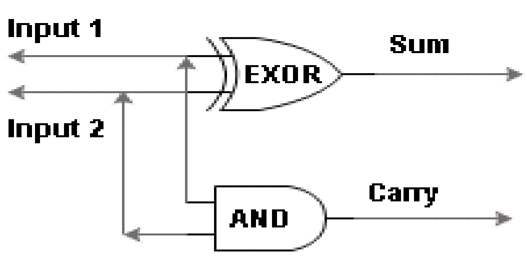

Fig. 3: *Schematic for Logical Half Adder.*

So to realize a half circuit with DNA logic, the basic DNA EXOR and AND gates have to be designed first.

Implementing EXOR Logic

As shown in Figure 4, a transcriptor EXOR logic element requires one asymmetric transcription terminator with two pairs of opposing recombination sites (TEs) recognized by independent integrases. When none of the integrase is present, the terminator will block the transcription as shown in Figure 4.

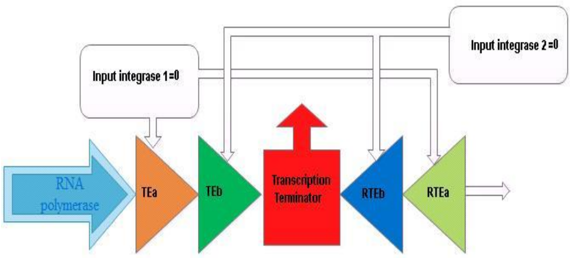

Fig. 4: Schematic for Logical DNA EXOR showing Blocked Transcription with Absence of Intergace 1 and 2.

Symbols: TEa and RTEa are associated with integrase 1; TEb and RTEb are associated with integrase 2, respectively.

Presence of any one of the integrase will invert the terminator and will modify a pair of transcription element which will allow the transcription current to flow (Figure 5). Whereas the presence of both the integrases will invert the terminator twice which will restore the terminator's original orientation and will block transcription again.

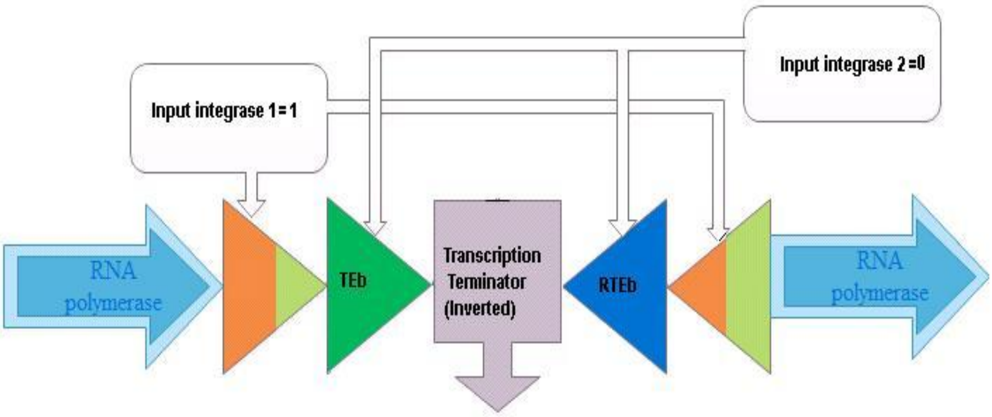

***Fig. 5:** Schematic for Logical DNA EXOR showing Transcription Continuation with Presence of Intergace 1 (=1).*

Implementing AND Logic

A transcriptor AND logic element requires two asymmetric transcription terminators with two pairs of opposing recombination sites (Transcription Elements) associated with each transcription terminator, as shown in Figure 5. The transcription current will flow only when both the intergaces will present but no transcription current flow if only one integrase is present as shown in Figure 6.

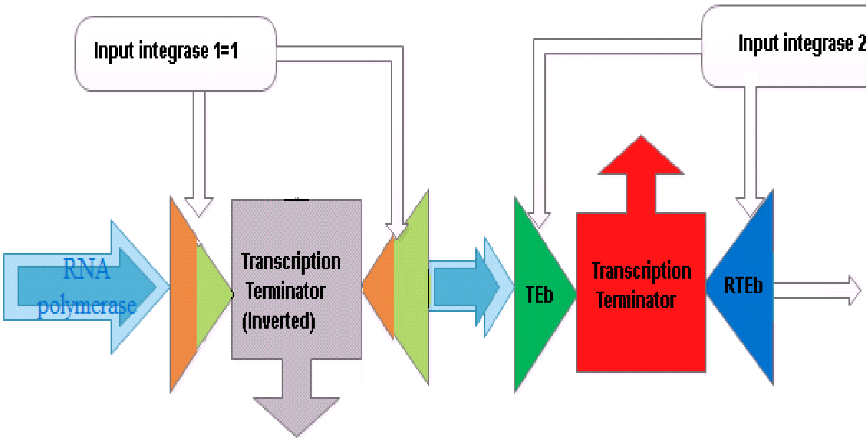

Fig. 6: *Schematic for Logical Representation of AND showing Blocked Transcription with Presence of Intergace 1 and Absence of Intergace 2.*

With further extension of this concept, other Boolean logics like NAND, NOR, OR, NOT can be also implemented with DNA logic [9–10].

RESULTS AND DISCUSSION

Under the present work, a half adder has been logically design and implemented with MATLAB Simulink and the timing diagram for sum and carry has been successfully simulated. The Simulink block diagram of the half adder has been presented in Figure 7. Where RNA polymerase has been considered as input signal and integrase 1 and 2 will from the logic inputs for the half adder.

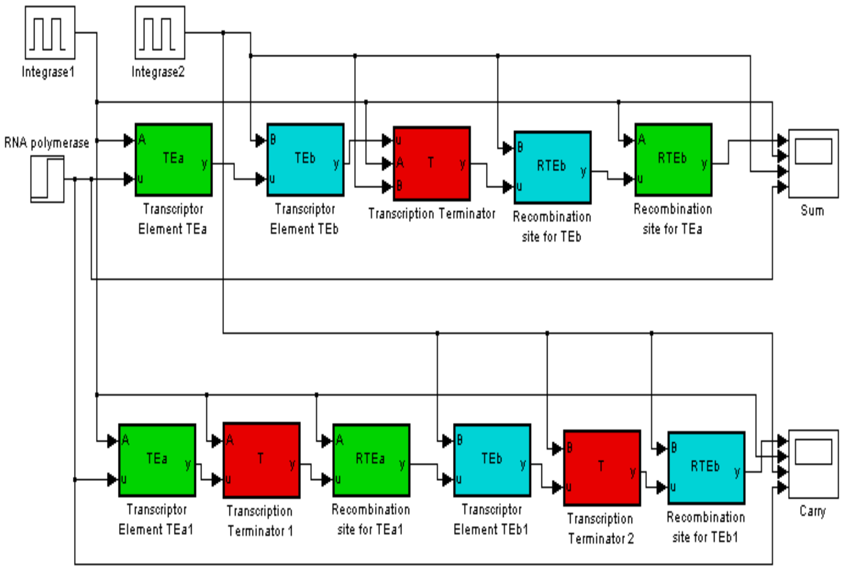

Fig. 7: *Simulink Block Diagram of Half Adder with EXOR at the Top and AND at the Bottom.*

To implement the half adder in Simulink user defined function block has been selected from library and every block is fitted with logical function to replicate transcriptor and transcription elements. Whereas the pulse source of variable widths have been considered for replicating integrase 1 and 2 and a unit step function has been selected to replicate RNA polymerase input

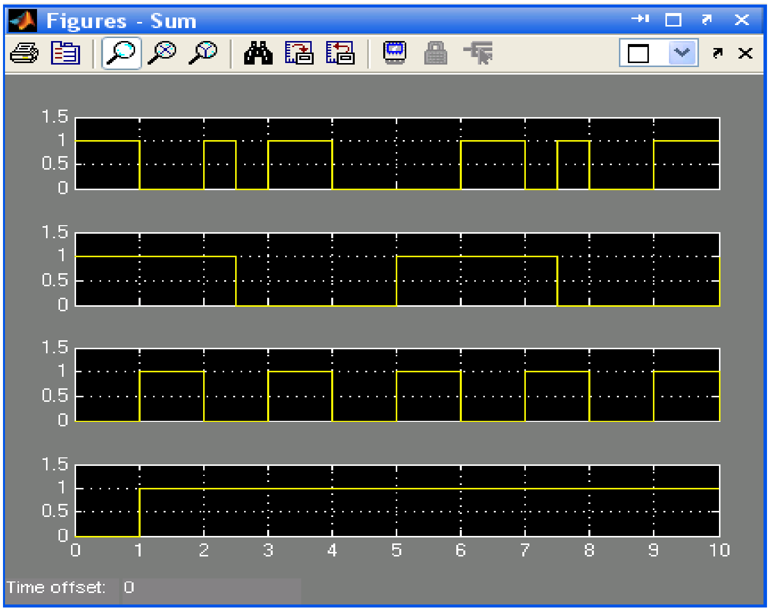

Fig. 8: *With Time the Sum, Integrase 1, Integrase 2, RNA Polymerase Input are Shown from Top to Down.*

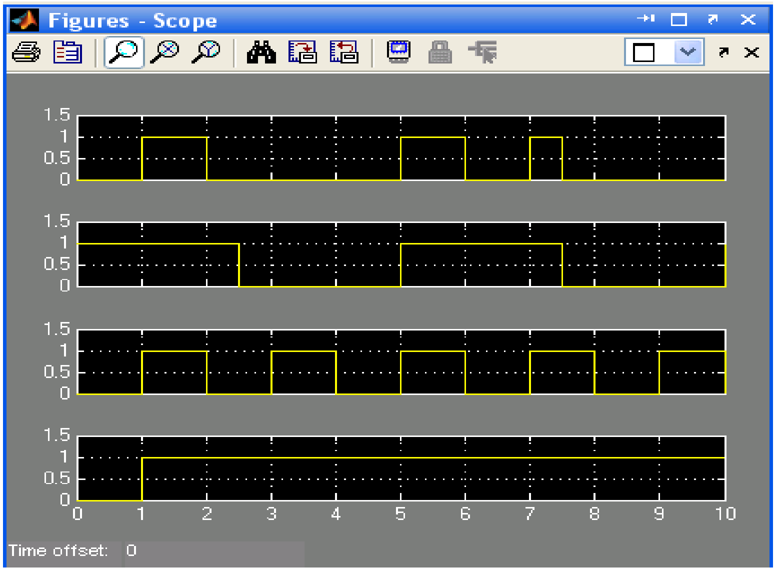

Fig. 9: *With Time the Carry, Integrase 1, Integrase 2, RNA Polymerase Input are Shown from Top to Down.*

Correlation of sum, carry with control signal integrase 1, integrase 2 and input signal (RNA polymerase) has successfully implemented half adder logic as shown in Figure 8 and Figure 9.

TABLE I.

Time Unit	Integrase 1	Integrase 2	Sum Simulated (Expected)	Carry Simulated (Expected)
3'	0	1	1(1)	--
3''	0	1	--	0(0)
7'	1	1	0(0)	--
7''	1	1	--	1(1)

a. Truth table for half adder

TABLE II.

Change in Time Unit	Change in Integrase 1	Change in Integrase 2	Change in Output	Sum (error in %)	Carry (error in %)
3'	0→0	0→1	0→1(sum)	4	--
3''	0→0	0→1	0→0 (carry)	--	8
7'	1→1	0→1	1→0(sum)	18	--
7''	1→1	0→1	0→1(carry)	--	7

b. Error percentage table for half adder

The Sum and Carry of the simulated half adder has been also verified with truth table (Table I, where Time unit from Figure 8 is indicated with single dash as superscript and from Figure 9 is indicated with double dash as superscript). A single cell may produce discontinuous responses to small changes in control signals which can be corrected with Population Measurements with n-number of cells. A digitization error rate can be defined as the combined probability of producing false high or low outputs in response to intermediate control signal changes. Based on the experimental analysis presented by Jerome Bonnet et.al.; the approximated digitization error percentage for EXOR gate from 1→0 and 0→1 input change is around 7%, 0→1 and 0→1 input change is around 15% etc. [10]. Where as for AND gate the approximated digitization error percentage is 10% for 1→0 and 0→1 input change, 8% for 0→1 and 0→1 input change etc. Based on those experimental results, the digitization error percentages have been calculated for the proposed half adder design and presented in Table II.

CONCLUSION

Under the present work the DNA logic gate design concepts has been theoretically investigated in detail.

The logical design concepts of EXOR and AND gate have been implemented with proper understanding and explanations. Finally a half adder has been logically designed with DNA based EXOR and AND gate with MATLAB Simulink model. The timing diagrams for the sum, carry, logic inputs and input signal are simulated.

The digitization error in percentage has also been approximated and presented for different input combinations for the half adder circuit. Such block level design of DNA half adder circuit will provide valuable understanding about the DNA based logic circuit design. Not only that such block level design can be added with proper mathematical model of DNA transistor which will initiate the development of future bioelectronics circuit simulators.

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