Implementation of Testable Reversible Sequential Circuit on FPGA

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Abstract: **The design of testable sequential circuits by two vectors using conservative logic. The proposed sequential circuits based on conservative logic outclass the traditional sequential circuits built using classical gates in terms of testability. Any sequential circuits based on conservative logic can test for stuck-at 0 and stuck-at 1 fault by using two vectors 0 and 1. The design of testable Master-slave D flip-flop, Double Edge triggered flip flop (DET) flip-flop using two vectors 0 and 1 are presented. The importance of the proposed work is that we are designing reversible sequential circuits suitable for testing. Hence both conservative logic and reversible logic is used. In the proposed work, we design a reversible sequential circuit using Fredkin gate. Fredkin gate is the only reversible gate which supports both conservative and reversible logic and also having less quantum delay.**

Index terms: **conservative logic, reversible logic, Fredkin gate, D flip-flop.**

I. INTRODUCTION

Conservative logic is a logic family that displays the property that there are equal numbers of 1's in the output as therein the input. Conservative logic can be reversible or may not be reversible in nature. By using conservative logic it has zero internal power dissipation which is an added advantage to this proposed technique. Reversibility is the property which shows one-to-one mapping between input and output vector; thus the vector of input states can be always reconstructed from the vector of output states. Reversible logic does not allow fan-out to occur, it means for each input corresponding output is produced. Hence for 1 input multiple outputs are not possible; this is strictly restricted by reversible logic which results testing to be easy. Conservative logic is also called reversible conservative logic when there is one-to-one mapping between input and output vectors along with the property that there are equal numbers of 1's in the outputs as in the inputs**.** If a circuit is designed in an irreversible manner then there will be a bit of information lost and which results in heat dissipation. The line of approach offered by conservative logic avoids a number of dead ends that are found in traditional models and opens up fresh views.

According to landauer principle one bit of information lost is equal KTln2 joules of energy lost, where K is the Boltzmann constant and T is the temperature in which operation is performed. So to reduce this energy lost completely we use reversible logic. And also reversible logic completely reduces heat dissipation. Reversible logic has received great attention in the recent years due to their ability to reduce the power dissipation which is the main requirement in low power VLSI design. Reversible logic takes care of Fan-out problem. It supports the process of running the system both forward and backward.

The proposed technique will take care of the **fan-out (FO)** at the output of the reversible latches and can also disrupt the feedback to make them suitable for testing by only two test vectors, all 0s and all 1s. By this way we can easily test the circuit with ease. In other words when circuit is executed in normal mode, feedback will be present because to compensate for the extra inputs. And similarly when executed in test mode its feedback is disrupted and the circuit is tested for stuck-at-faults. So proposed technique is divided in to two modes normal and test mode. Fan-out leads to increased capacitive load on the driving gate, and therefore longer delay. So the fan-out problem is taken care by the proposed technique. The proposed technique is extended toward the design of two vectors testable master-slave flip-flops and double edge triggered (DET) flip-flops.

Reversibility in computing implies that no information about the computational states can ever be lost, so we can recover any past stage by computing backwards or un-computing the results. This is termed as logical reversibility. The advantages of logical reversibility can be gained only after employing physical reversibility. It is a process that dissipates no energy to heat. Absolutely perfect physical reversibility is practically not possible. A circuit is said to be reversible if the input vector can be uniquely recovered from the output vector and there is a one-to-one correspondence between its input and output assignments, that is not only the outputs can be uniquely determined from the inputs, but also the inputs can be regained from the outputs.

In this paper we will be discussing in section-II about the different reversible logic gates and a detailed explanation of Fredkin gate which is common to both conservative and reversible logic. And section-III explains about the related works undertaken in this project. Section-IV deals with design of testable D latch, master-slave D flip-flop, DET flip flop. Section-V deals with the future enhancement and section-VII deals with the conclusion to the project.

II. REVERSIBLE LOGIC GATES

A reversible logic gate is an n-input n-output logic device with one-to-one mapping. This helps to find out the outputs from the inputs and also the inputs can be uniquely regained from the outputs. In reversible circuits, direct fan-Out is not allowed as one–to-many concept is not reversible. Also fan-out in reversible circuits is achieved using extra gates. A reversible circuit should be designed using minimal number of reversible logic gates. From the approach of reversible circuit design, there are many factors for determining the complexity and performance of circuits.

[1] The number of Reversible gates (N): The number of reversible gates used in circuit.

[2] The number of constant inputs (CI): This refers to the number of inputs that are to be preserved constant at either 0 or 1 in order to produce the given logical function.

[3] The number of garbage outputs (GO): This refers to the number of unused outputs present in a reversible logic circuit. Also the garbage outputs as these are very essential to achieve reversibility.

[4] Quantum cost (QC): This refers to the cost of the circuit in terms of the cost of a primitive gate.

There are different reversible gates and they are:
- Not gate
- Feynman gate (CNOT)
- Fredkin gate (CSWAP)
- Toffoli gate
- Peres gate
- Sayem gate
- Double Feynman gate

In this Toffoli gate and Fredkin gate are universal gates. Universal gates means using these gates any type of Boolean expression can be obtained (i.e.) any type of circuits can be designed. Not gate is the basic reversible gate. Feynman gate is a 2*2 one through reversible gate. The input vector is I (A, B) and the output vector is O (P, Q). The outputs are defined by P=A, Q = A $\oplus$ B. Toffoli gate is a 3*3 gate, the input & output vector is I (A, B, C), O(P,Q,R). The outputs are defined by P=A, Q=B, R=AB $\oplus$ C. NOT gate is an inverter which inverts the input. Likewise other gates are known. In this we select Fredkin gate mainly because it is compatible with both reversible and conservative logic.

A. FREDKIN GATE

Fredkin gate is a 3*3 gate shown in Fig 1. The input vector is I (A, B, C) and the output vector is O (P, Q, R). The output is defined by P=A, Q=A′B $\oplus$ AC and R=A′C $\oplus$ AB. Quantum cost of a Fredkin gate is 5. It is used for designing sequential circuits because it is the only common gate that can be used in conservative, switch, interaction and reversible logic. Due to its unique characteristics and properties Fredkin gate is used for designing sequential circuit and also it reduces delay and area used for designing a circuit. It is reversible and Conservative in nature,(i.e.) it has unique input and output mapping and also has the same number of
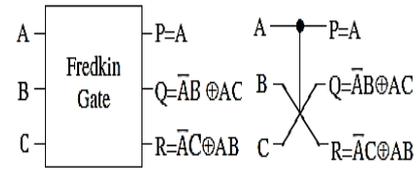

Fig1. Fredkin gate

1's in the outputs as in the inputs. Fredkin gate has three inputs, depending on the first input which is a control signal outputs are produced. If the first input is 1 means then the other two inputs are regained as outputs. If the input is 0 then the other two inputs are swapped and produced as outputs.

B. RELATED WORK

Any nanotechnology having applications of reversible logic, such as based on nano-CMOS devices, low power molecular QCA computing, or NMR-based quantum computing, all are vulnerable to high error rates due to transient faults. With regard to this paper on reversible sequential circuits, the model of reversible sequential circuits is addressed in the various interesting contribution in which the designs are improved in terms of various functions, such as the number of reversible gates, quantum cost, garbage outputs, delay etc. To the best of our understanding, the offline testing of faults in reversible sequential circuits is not addressed in the literature. In this paper, we present the design of reversible sequential circuits that can be tested by only two test vectors, all 0's and all 1's, for any unidirectional stuck-at-faults. By giving all the inputs as 1 we test for stuck-at-0 fault and similarly if we give all the input as 0 means we test for stuck-at-1 fault.

III. PROPOSED SYSTEM

A. DESIGN OF TESTABLE REVERSIBLE D LATCH

The characteristic equation of the D latch can be written as $Q+ = D \cdot E + .E \cdot Q$. In the proposed work, enable *(E)* refers to the clock and is used conversely in place of clock. When the enable signal (clock) is 1, the value of the input D is reflected at the output that is $Q+ = D$. While, when $E = 0$ the latch preserves its previous state, that is $Q+ = Q$. In Fig. 2(a) reversible D latch is shown and its characteristic equation is reverse of D latch characteristic equation but that design cannot be tested only by two vectors because of feedback. Some misinterruptions may occur.

So in our proposed work we will cascade two Fredkin gate and Q output of one gate will follow the other. And it has two control signals C1 and C2 by which the design works. In normal mode which is shown in Fig. 2(b) works when C1 and C2 is given as 0 and 1 and the circuit works as a D latch without any fan-out problem. In test mode which is shown in Fig. 2(c) and (d) works when C1 and C2 is given as

1 and 1 or 0 and 0, the circuit disrupts the feedback and checks for stuck-at-0 or stuck-at-1 fault.

B. DESIGN OF TESTABLE NEGATIVE ENABLE D LATCH

A negative enable reversible D latch will pass the input D to the output Q when $E = 0$; otherwise preserves the previous state. The characteristic equation of the negative enable D latch is $Q+ = D \cdot E + E \cdot Q$. This characteristic equation of the negative enable reversible D latch can be mapped on the second output of the Fredkin gate. The next Fredkin gate in the design take cares of the FO. This Fredkin gate in the design also helps in making the design testable by two test vectors, all 0's and all 1's, by breaking the feedback based on control signals C1 and C2 as illustrated above for positive enable D latch. The negative enable D latch is helpful in the design of testable reversible master-slave flip flops. This is because as it can work as a slave latch in the testable reversible master-slave flip-flops in which no clock inversion is required.

C. DESIGN OF TESTABLE MASTER-SLAVE FLIP-FLOPS

We have proposed the design of testable flip-flops using the master slave strategy that can be tested for any stuck-at faults using only two test vectors, all 0s and all 1s. Master latch will be positive enabled Fredkin gate based D latch and slave latch will be negative enabled Fredkin gate based D latch. Fig 4 shows the master-slave D flip flop. There are 4 control signals sC1, sc2, mC1 and mc2. mC1 and mC2 control the master latch and similarly sC1 and sC2 control the slave latch. When signals are given as 0 and 1 it will work in normal mode and avoid fan out problem. If the signals are given 0 and 0 it will disrupt the feedback and test the circuit for stuck-at-1 fault. Suppose if the signals are given as 1 and 1 then it will test the circuit for stuck-at-0 fault. Here Master controls the slave latch. If signal is given as 1 master latch works and vice-versa slave latch will work.

D. DESIGN OF TESTABLE REVERSIBLE DET FLIP-FLOPS

In the master-slave flip-flop, it does not sample the data at both clock edges; instead it waits for the next rising edge of the clock to work as a master or slave latch. In order to overcome the abovementioned problem, researchers have introduced the concept of DET flip-flops which sample the data at both the edges. Thus, DET flip-flops can sample and receive two data values in a clock period thus frequency of the clock can be reduced to half of the master- slave flip-flop while maintaining the same data rate. The half frequency operations make the DET flip flops very much useful for low power computing as frequency is equal to power consumption in a circuit. It is designed by connecting the two latches, via, the positive enable and the negative enable in parallel rather than in series. The 2:1 Multiplexer at the output transfer the output from one of these latches which is in the storage state (is holding its previous state).
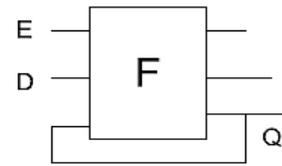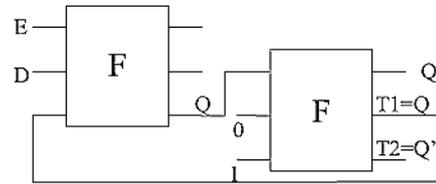

Fig2(a). reversible D latch
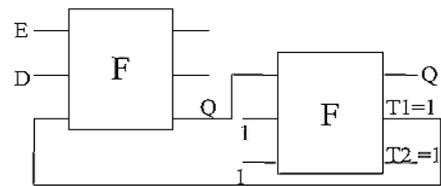

Fig2(b). Normal mode
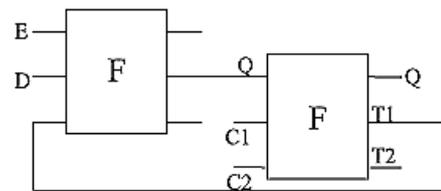

Fig2(c.) test mode for stuck-at-0 fault

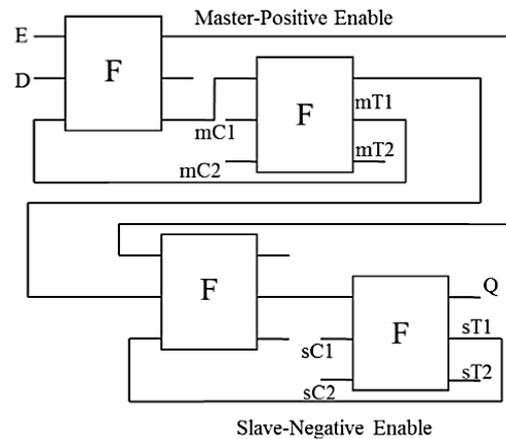Fig2(d). test mode for stuck-at-1 fault

Fig4. Master-slave D flip-flop

In the proposed design of testable reversible DET flip-flop, the positive enable testable reversible D latch and the negative enable testable reversible D latch are set up in parallel. The Fredkin gates labelled as 1 and 2 forms the positive enable, while the Fredkin gates labelled as 3 and 4 forms the negative enable testable D latch. In reversible logic Fan-out is not allowed so the Fredkin gate labelled as 6 is used to copy the input signal D. The Fredkin works as the
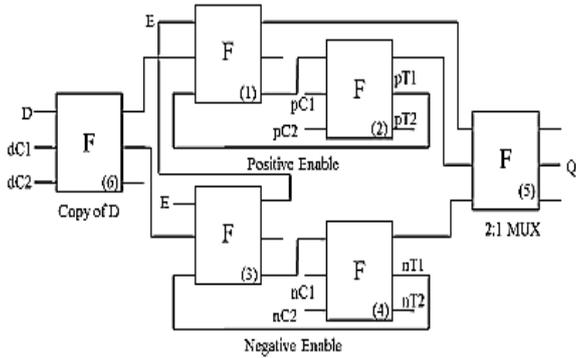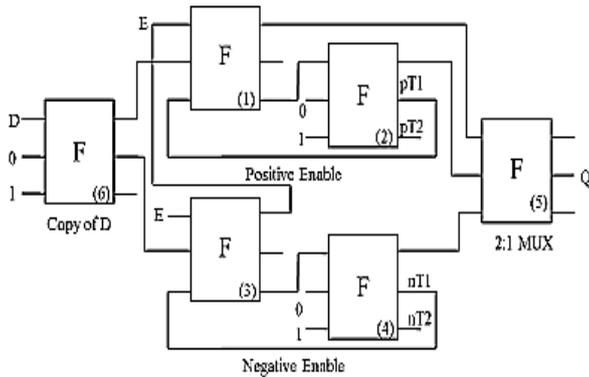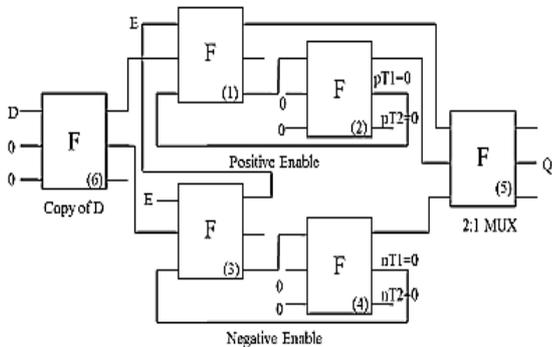
Fig5. DET flip-flop

Fig5(b). normal mode

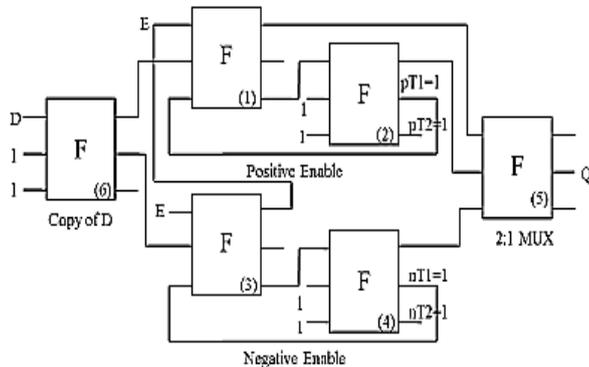*Fig5(c). test mode for stuck-at-1 fault*

Fig5(d). test mode for stuck-at-0 fault

2:1 MUX and transfer the output from one of these testable latches (negative enable D latch or the positive enable D latch) that is in the storage state (is holding its previous state) to the output Q. In the proposed design of testable reversible DET flip-flop, nC1 and nC2 are the controls signals of the testable negative enable D latch, while pC1 and pC2 are the control signals of the testable positive enable D latch. Depending on the values of the pC1, pC2, nC1, and nC2, the testable DET flip-flops work either in normal mode or in the testing mode.

In normal mode pC1 and pC2 are given as 0 and 1 and similarly nC1 and nC2 are given as 0 and 1. The $pC1 = 0$, $pC2 = 1$ help in copying the output of the positive enable D latch thus avoiding the Fan-out while the $nC1 = 0$ and $nC2 = 1$ help in copying the output of the negative enable D latch thus avoiding the FO. Similarly in test mode if all signals are given as 0 then it tests the circuit for stuck-at-1 fault. If all the signals are given as 1 then it tests for stuck-at-0 fault.

V. FUTURE ENHANCEMENT

In the proposed system we have designed sequential circuits using Fredkin gate. As sequential circuit has feedback it supports reversible logic and hence we designed circuits using reversible logic gate. So in future I would be designing combinational circuits which are irreversible using reversible logic. And also there is an advanced and a complex gate than Fredkin gate which is used in nano technology that is MX-QCA gate also will be designed and corresponding circuits using that gate will be designed.
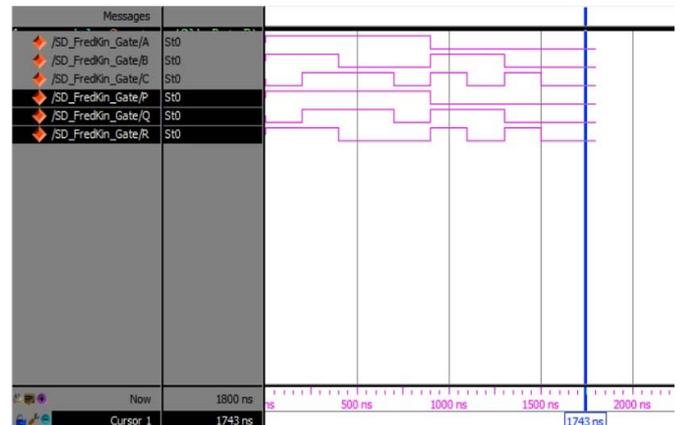
VI- OUTPUTS

Fig 6. Fredkin gate

In the above output we can see the output of Fredkin gate. So if the control signal is given as 1 then the two outputs obtained is same as the inputs. Similarly if the control signal is given as 0 then the 2 outputs obtained is the swapping of inputs. This output is obtained through modelsim software. And similarly other designs are written using Verilog coding and output is obtained using modelsim software.
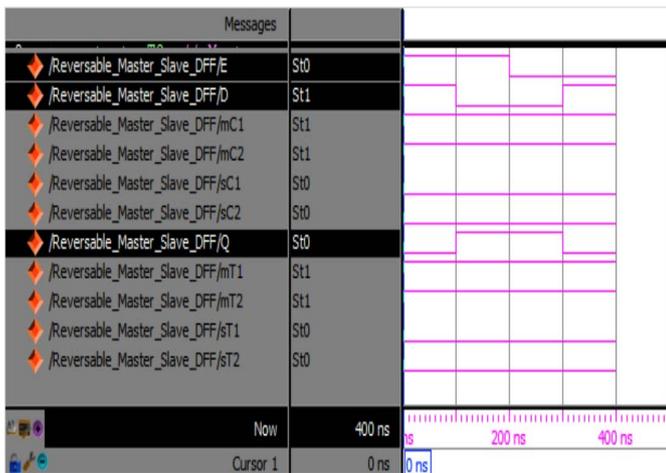
Fig7. Master-slave flip-flop

From the above output we can see that if control signal or given as 1 means master latch will produce the positive enabled D latch output and similarly 0 means slave latch will produce the negative enabled D latch output.

VII. CONCLUSION

Thus Reversible sequential circuits are designed using reversible and conservative logic successfully and tested for stuck-at-faults. A design of Fredkin gate, testable D latch using Fredkin gate, Master slave flip-flop using Fredkin gate, DET flip flop is designed. It is made testable only using two vectors 0 and 1 and so complexity is reduced. In future reversible and conservative logic will be designed for combinational circuits and implemented and will be tested for faults. Thus, the main advantage of the proposed conservative reversible sequential circuits compared to the conventional sequential circuit is the need of only two test vectors to test any sequential circuit irrespective of its complexity. The reduction in number of test vectors minimizes the overhead of test time for a reversible sequential circuit.

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