

An efficient Sense amplifier based Flip-Flop design

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Abstract—

An efficient approach for sense amplifier based flip-flop design has been introduced in this paper. It was found that the main speed bottleneck of existing SAFF's is the cross-coupled set-reset (SR) latch at the output stage. To make the sense amplifier more efficient, we designed a clocked CMOS based latch for the sense amplifier. We surveyed on the design of Sense Amplifier and their experimental evaluation presented. The simulation results were compared in terms of timing parameters, switching activities and the power dissipation etc. with conventional flip-flop and hybrid approach has been presented in this field. We have done the minimum sizing of transistors and also designed the layout for them. Net lists with parasitic capacitance were extracted from layouts and simulated using MENTOR GRAPHICS, Tsmc 0.25um technology. We applied the sinusoidal clock of single phase of 200 MHz frequency generated by clock generator of high efficiency. The designed circuit provides ratio less design, reduced short-circuit power dissipation, and glitch-free operation. The power delay product (PDP) is improved by 50.54%, 17.95% and 25.21% in comparison to conventional flip flop for switching activity $\alpha=1, 0.5$ and 0.25 respectively. A PDP improvement of 14.9 %, 13.66% and 8.72% is also reported in comparison with hybrid approach. Finally the approach indicates the flip-flop's suitability with low power and high performance based designs.

Index Terms—Clocked CMOS, CMOS digital integrated circuits, flip-flops, sense amplifier, PDP.

I. INTRODUCTION

FLIP FLOPS are ubiquitous elements in CMOS circuits based designs which make the major portion of the synchronous circuits. As a result, the structure of FF used in circuits has a large impact on system power consumption. Moreover, the type of FF used determines the amount of clock load, which directly affects dynamic power consumption P_{DYN} of a circuit.

Thus, it is prudent to come up with techniques to reduce the power consumption of FFs to reduce the overall system power Consumption [1]. Also the power dissipated in clock distribution network is 30% to 60% of the total system power, where 90% of which is consumed by the flip flops and the CDN that is driving the flip flops [2]. As the power budget of today's portable digital circuit is severely limited, it is important to reduce the power dissipation in both CDN and in the flip flops.

Timing elements, latches and flip flop are critical for the performance of the digital systems because of the tight timing constraints and requirements for low power [3]. Short set up and hold times are also required for performance, but often overlooked. In a complex system it is very often necessary to have the ability to scan the data in and out during the test and diagnostic process.

For high performance increase the clock frequency with the technology scaling. But in deep sub micrometer generation's higher performance is obtained by parallelism in the architecture level (eg. Multicore architectures for processor [4]). Deeply pipelined systems exhibit inherent parallelism that requires higher fan-outs at the register outputs. This impacts the requirements for higher flip-flop driving strengths. The impact of the clock skew on the minimum cycle time increases in deep sub micrometer designs as the clock skew does not follow the technology scaling. Thus the ability to absorb the clock skew without impact on setup time becomes important. The amount of cycle time taken out by the flip-flop consists of the sum of setup time and clock-to-output delay [5]. Therefore, the true measure of the flip-flop delay is the time between the latest point of data arrival and corresponding output transition.

In this work we extensively studied the existing flip flops architectures, analyzed and proposed a new sense amplifier based flip flop circuits. SAFF is differential in character, fast in speed and consume low power. The SAFF circuit is implemented by the various circuits such as microprocessors, digital signal processing units etc. In Section II, we present mechanism, timing definitions and tools used in the process. Section III presents the working of the proposed design latch of the sense amplifier. Section IV presents the analysis, observation and comparison with SR flip flop by simple CMOS design, clocked CMOS based design and a hybrid

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solution between the standard NAND-based set/reset latches and NC²-MOS approach. In section V results and conclusions are discussed.

II. SENSE –AMPLIFIER BASED FLIP FLOP

A. Mechanism

The fig [1] shows the general mechanism of flip flop operation. It is different than the master-slave flip flop that consists cascading of two latches) and glitch approaches. The master-slave flip flop creates problem if the clock phases overlaps.

Sense amplifier circuits accept small input small signals and amplify them to generate small rail to rail swings. They are used extensively in memory cores and in low swing bus drivers to either improve performance or reduce power dissipation.

In general the flip flop operation can be divided in two parts that is mentioned in the fig [1] in two blocks. A pulse generator (or precharged front end amplifier [6]), and a slave latch, similar to the master-slave latch combination consist master and slave latch.

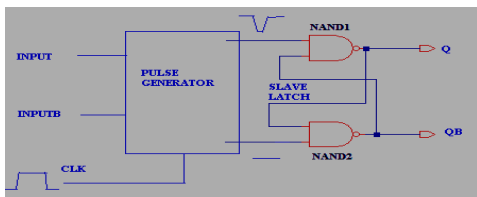


Fig: 1 Basic structure of flip flop

In pulse generator the inputs are the data and clock. The pulse generator generates short pulses of sufficient duration. This pulse in turn sets the slave latch. The pattern generator generates the pulse according to the particular realization of the rising or falling edge of clock. The use of cross coupled inverter guarantees that the differential output will switch only once per cycle. The differential inputs in this implementation don't have to have rail to rail swing. While M-S latch is level sensitive. The sensitivity of pattern generator may pose danger under certain conditions in terms of reliability and robustness of operation. Thus the use of flip flop has been prohibited in some design methodology such as IBM's LSSD [7].

B. Timing, tools and technology used:

Fig [2] represents the timing definition for all the observations. We considered the reference point for all the observations in rising edge of the clock from half of the supply voltage.

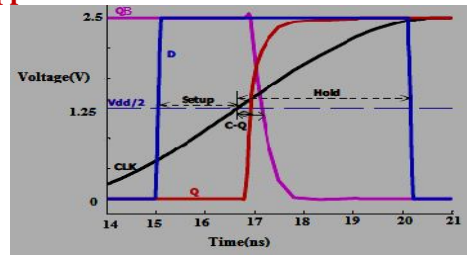


Fig: 2 sample waveforms for timing definition

The fig [3] represents the timing requirements to send the correct data to output.

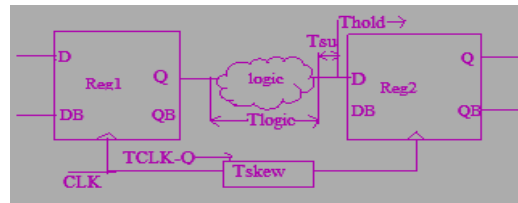


Fig 3: Timing requirements

Set up time is defined as the time from when the data is stable before the rising edge of the clock.

$$T_{su} \geq T_{CLK-Q} + T_{logic} + T_{hold} \quad \dots(1)$$

It imposes an extra constraint for proper operation. Hold time is defined as the time from the rising transition of clock to the earliest time when data may change after being sampled.

$$T_{hold} \leq T_{CDreg} + T_{CDlogic} \quad \dots\dots\dots (2)$$

From fig [2] hold time will be negative and large, since the data is held before the clock edge.

The CLK-Q delay is defined as the time from the half of the rising edge of the CLK to the more delayed output (here QB) to verify the timing definition. The D-Q delay is defined as time from the point where D transition reaches 50% of the supply voltage to the point where the Q transition reaches 50% of the supply voltage.

We simulate all the SAFF with MENTOR GRAPHICS DA tool in 0.25um technology with a supply voltage of 2.5V. The design was optimized at temperature of 27°C for a clock frequency of 200MHz, and a load capacitance of 30fF was used for the output Q.

Section III

A. Conventional NAND gate based latch in SENSE AMPLIFIER

This flip flop is a dynamic flip flop with precharge and evaluates phases of operation discussed in [8]. In [9] this flip flop is used as an energy recovery flip flop to recover the energy from clock distribution network and clock input capacitance of flip flops. Since clock signal is highly capacitive. Recovering the energy from internal nodes of flip flops in a quasi adiabatic fashion is required. However, storage elements of flip flops cannot be energy recovering because they drive standard (non adiabatic) logic. Due to slow

rising /falling transition of the clock signal there is the possibility of

short circuit in the storage elements during recovering the energy from clock distribution network. In [2] this flip flop is used to operate with the low voltage swing clock. The fig [4] represents the schematic of sense amplifier based flip flop with the minimum sizing.

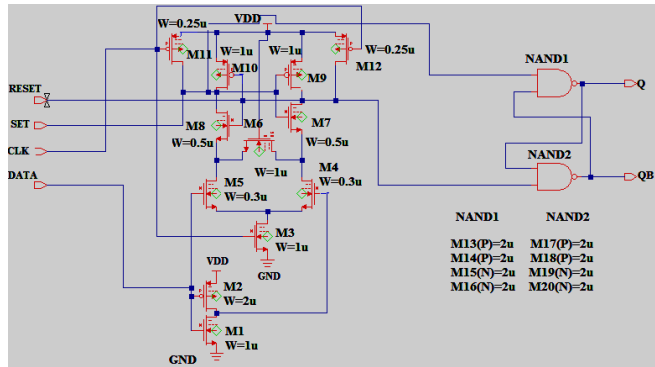


Fig: 4 Sense Amplifier with NAND based SR latch

When CLK goes high \rightarrow low the precharge occurs at his point the potential of the clock reaches $V_{DD}-V_{tp}$, where V_{tp} is the threshold potential of precharging PMOS transistors (M11 and M12). Since SET and RESET nodes are high that will not change the output of the feedback cross coupled NAND gate. When the clock voltage exceeds the threshold voltage (V_m) of M1 the evaluation occurs. At the onset of evaluation, the difference between the differential inputs (D and DB) results in small voltage difference between set and reset nodes. This initial small voltage is then amplified by the cross coupled inverter and as a result either set or reset node switches to low.

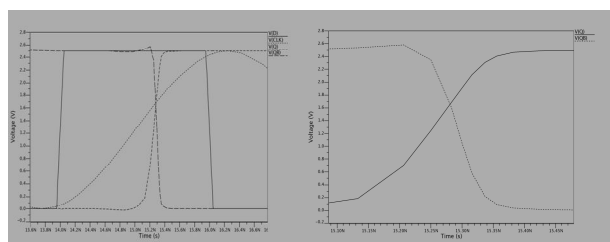


Fig: 5 simulated output with timing definition

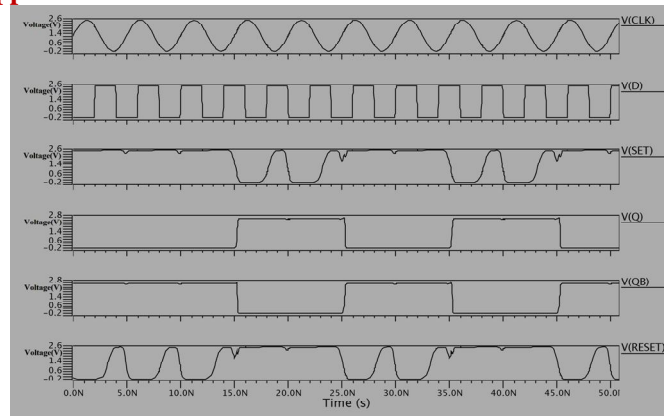


Fig: 6 simulated output of SAFF with NAND based SR latch at output

When D is high the SET node discharges to ground through three stacked NMOS transistor (M8, M5 and M3), that causes output Q to charge to 1. Due to cross coupled inverter RESET node is high. This state transition is captured by the SET/RESET latch (made of NAND gates) and retained for the rest of the cycle time until the next evaluation occurs.

SAFF has delay penalty. This is due to two reasons: The use of three stacked NMOS transistors and the low speed of static output latch. The SAFF performs very well in terms of power dissipation and high data switching activity due to minimum sizing and stacking effect. However it consumes unnecessary power even when the data input does not change for low data switching activity. Internal nodes SET/RESET are always precharged continuously when the clock is low. Suppose if the data is high for long time than SET/RESET node always charge to VDD and discharge through the path M8, M5, and M13 on rising edge of the clock. The M6 transistor will always be on and provides the DC leakage path for both SET/RESET nodes to ground. Consequently internal nodes of SAFF charge/discharge regardless of the input condition. The total power consumption can be significantly reduced by avoiding such redundant internal switching [10].

B. Hybrid approach

The output latch of the sense amplifier is replaced by the standard NAND based SR latch and NC²MOS approach [11]. In [12] Kim et al. proposes a SAFF that uses a slave latch with two NC²MOS circuits and two cross coupled weak inverter pairs, which are needed to make the flip flop static. But it has some disadvantages. It has glitches and more power dissipation at the output due to crow bar current. The fig [7] represents the schematic of Strolgio based latch. We used this with the single phase sinusoidal clock for low power application.

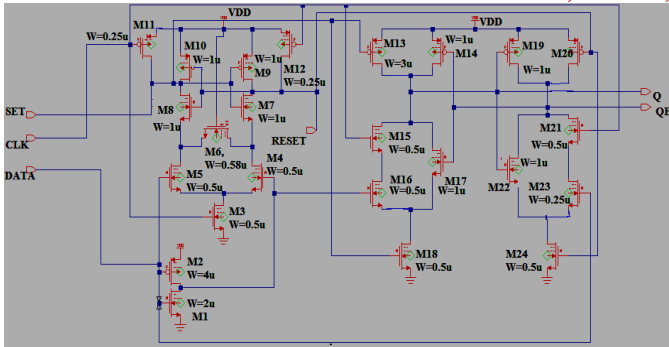


Fig: 7 Antonio based SAFF

Circuit Operation: If we remove transistor M15, M16, M21, M23 than it will become NAND based SR latch. When D is high at the rising edge of clock the sense amplifier drives SET node to zero, while RESET is high due to feed back inverter. M13 will be on and M18 will be off that makes the output Q high and QB is quickly pulled down to 0 through M21, M23, and M24. Hence the H→L output transition requires only one

stage output delay, because the output latch immediately catches the precharged value at the rising edge of the clock. The role of M14, M17, M18, M19, M22, M24 hold the previous value of Q and QB during the sense amplifier precharge, making the flip flop fully static. The role of transistor M16 and M23 makes the design glitch free. Suppose for instance CLK L→H transition occurs with both Q and D high. After the CLK rising edge, the SET node is still high and transistor M18 is on. Since M16 is off so the node Q always remain at VDD, without glitch.

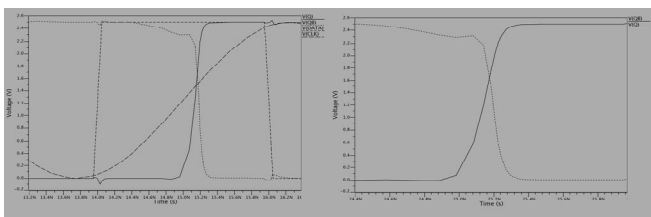


Fig: 8 simulated glitch free output with timing definition

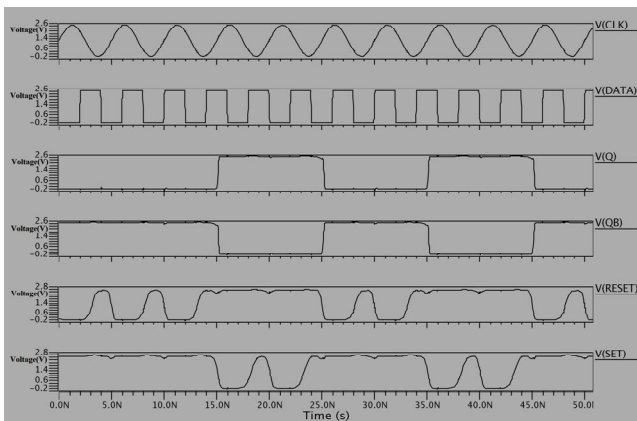


Fig: 9 simulated output of Antonio based flip flop

C. Clocked CMOS based design

1) First approach

A clocked CMOS version of the latch is shown in fig [10]. It consists of a cross coupled inverter pair, plus inverter and NMOS transistor at both Q and QB and four extra transistors to drive the flip flop from one state to another, and to provide synchronization. The role of INV1, INV2, M17 and M18 at output is to reduce the redundant Internal switching at output. In steady state one inverter resides in the high state and other in the low state. No static path between VDD and GND exists. Transistor sizing is however essential to ensure that the flip flop can transition from one state to other if required.

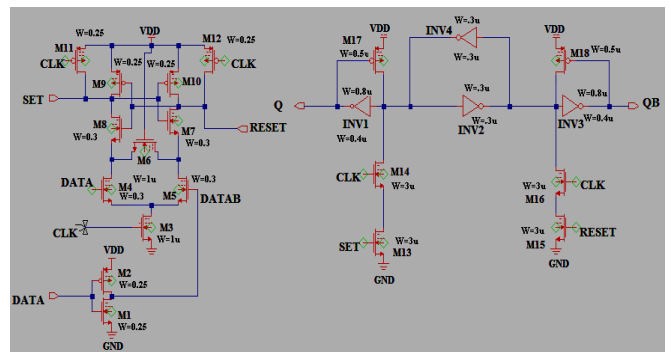


Fig: 10 Clocked CMOS based approach

To describe the circuit operation let us assume, that D is high at the rising edge of CLK. The sense amplifier drives SET to 0, while RESET remains high and in this way M13 off and M15 on driving QB high. Note that the shut off of M13 assures at the same time a ratio less design, without crow bar current and the independence of the transition delay from the capacitive load on the other Q output. The use of feedback inverter quickly discharges the QB through inv2 and makes the output Q to high. The H→L transition requires only one stage delay because the output latch catches the precharged value at the rising edge of the CLK. Note that if, after pull up of QB, PMOS of inv4 turns on, keeping QB high even if input D changes after CLK rising edge. The use of inv2 and inv4 hold the previous Q and QB value during the sense amplifier precharge, making the flip flop fully static. The output of the proposed design is presented in fig [11].

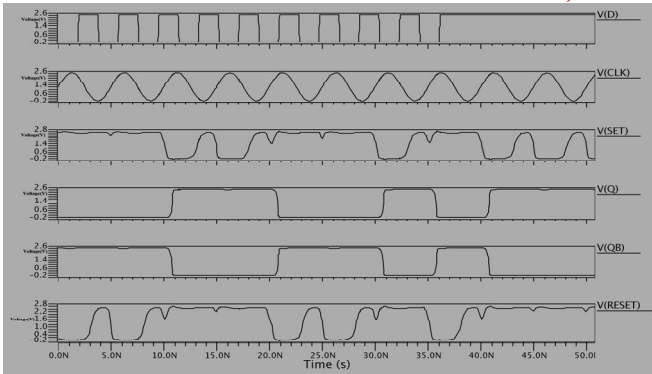


Fig: 11 simulated output of the proposed design

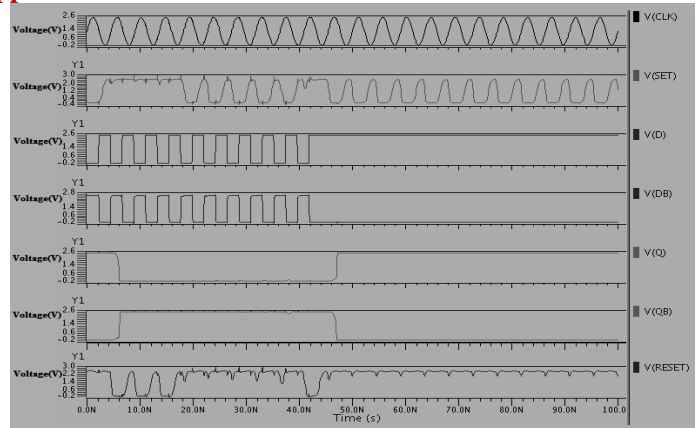


Fig 14: simulated output of second approach

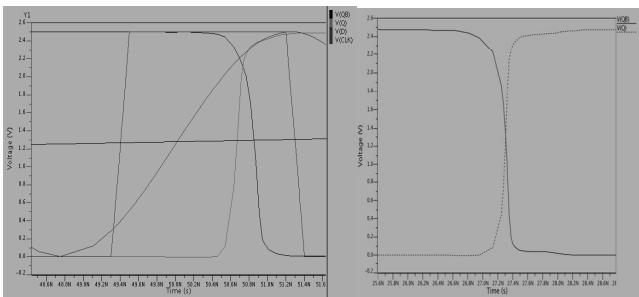


Fig: 12 simulated output with timing definition (first approach)

2) Second approach

Fig [13] represents the schematic of the design. The working is same as described above. Here we added two NMOS transistor in the first approach, in which the inputs are D and DB. It enables the avoidance of glitch problem. Let us suppose that at clock rising edge both QB and D is high. After the CLK rising edge, the SET node is still high and transistor M15 is on. However, the pull down through

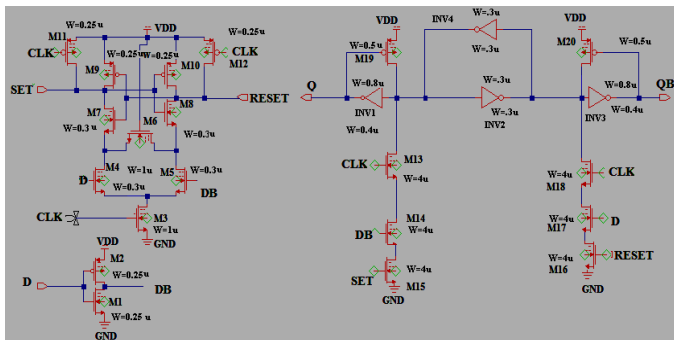


Fig 13: Schematic of second approach

The speed-up network M13-14 does not take place, since M14 is off. As a consequence QB will be stable at VDD and Q at 0 without glitch. The absence of glitches at the output gives the safe operation and reduces power dissipation.

IV. Analysis and Observations

SAFF	CLK-to-output delay L? H? L	Rati oless	Q and QB delay independence	Glitch free output	Output noise immunity	Robustness against sizing	Dual Outputs
conventional	2stages 3stages	Yes	No	Yes	No	Yes	Yes
Nikolic et al.	2stages 3stages	Yes	Yes	Yes	No	Yes	Yes
Kim et al.	2stages 1 stage	No	Yes	No	No	No	Yes
Antonio et al.	2stages 1 stage	Yes	Yes	Yes	No	Yes	yes
Proposed	2 stages 1 stage	Yes	Yes	Yes	No	Yes	Yes

Table 1: (Flip-flop characteristics)

Design	Total width of pulse generator (with inverter) μm	Total width of Output latch μm	Total width μm	Total no. of transistor used in output latch	Clock used
Conventional 1NAND based SR latch	9.1	16	25.1	8	Sinusoidal single phase
Matsui et al. and Montanaro et al.	-	-	54.9	8	Square wave
Antonio et al.	12.58	10.75	23.33	12	Sinusoidal single phase
	-	-	44.5	12	Square wave
Proposed (II)	4.7	28.6	33.3	16	Sinusoidal single phase
Nikolic et al.	-	-	67.8	16	Square wave
Kim et al.	-	-	58.4	14	Square wave

Table 2: (Flip-flop measurements)

Data pattern (α)	T_{su} (ns)	T_{hold} (ns)	T_{rQ} (ns)	T_{fQ} (ns)	Total power dissipation (μwatt)	PDP (fJ)	Flip flops
0101010 101010101 0011001 100110011	1	0.79	0.21	1.2	42.97	52.08	Conventional NAND based SAFF
0000111 100001111	0.58	1.48	0.23	0.81	42.97	34.81	
0101010 101010101	0.44	1.08	0.37	0.78	42.97	33.51	
0011001 100110011	0.49	1.2	0.197	0.69	42.96	29.6	
0000111 100001111	0.58	1.48	0.193	0.77	42.96	33.08	Antonio et al.
0101010 1010101	0.44	1.08	0.196	0.64	42.96	27.5	
0101010 1010101	1	0.8	0.38	0.70	36.8	25.76	Proposed (II)
0011001 1001100	0.6	1.4	0.35	0.80	35.7	28.56	
0000111 100001111	0.58	1	0.3	0.70	35.8	25.06	

Table 3: Represents the PDP and timing parameters for different switching activities $\alpha=1, \alpha=0.5, \alpha=0.25$ for sinusoidal clock of 200 MHz and the output load in the range of 30fF-200fF.

Table 1 represents the characteristic of proposed and others.

The CLK to output delay for H→L transition of Q or QB is one gate delay because the output is immediately appears at the rising edge of CLK; however the delay of two feedback inverter will also be associated in both approaches.

Table 2 represents the minimum sizing, the no. of transistor used in pulse generator and output latch with respect to different clock. We used sinusoidal clock for comparison. Table 3 represents the PDP and CLK-Q delay for various flip flops and the proposed one with switching activity. The proposed flip-flop is best one for both the Power

and performance. The design can be sized to work with other frequencies.

V. CONCLUSION

This paper introduces new sense amplifier based flip-flop. The slave latch of the new flip-flop is able to keep the advantage of NC²MOS approach [15]. The future work can be extended by giving the preset and clear to achieve asynchronous flip-flop. The design can be used as an energy recovery flip-flop since it is assumed that only the storage part of element of flip flop cannot be energy recovering because they drive standard (non-adiabatic) logic [9]. But the energy at the gates of sense amplifiers can be used for energy recovery, since they are not the part of storage element. However, the proposed design is more efficient due to feed back inverters used and consumes lesser total power when compared with conventional and Hybrid flip-flops.

The proposed flip-flop gives a very good PDP with glitch free operation, lesser crow-bar current and lesser static power dissipation.

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REFERENCES

- [1] F. Moradi, C. Augustine, A. Goel, G. Karakonstantis, T. V. Cao, D. Wisland, H. Mahmoodi, and K. Roy "Data dependent Sense Amplifier Flip Flop for low Power application," *IEEE Con.* 2010.
- [2] H. Kawaguchi and T. Sakurai, "A reduced clock swing flip flop (RCFF) For 63% power reduction," *IEEE J. Solid-State Circuits*, vol. 33, pp. 807–811, May 1998.
- [3] G. Gerosa *et al.*, "A 2.2W, 80 MHz superscalar RISC microprocessor," *IEEE J. Solid-State Circuits*, vol. 29, pp. 1440–1452, Dec. 1994.
- [4] S. Rusu, S. Tam, H. Muljono, D. Ayers, J. Chang, B. Cherkauer, J. Stinson, J. Benoit, R. Varada, J. Leung, R. D. Limaye, and S. Vora, "A 65-nm dual core multithreaded xeon processor with 16-MB L3 cache," *IEEE J. Solid State Circuits*, vol.42, no.1, pp. 17-25, Jan. 2007.
- [5] S. H. Unger and C. J. Tan, "Clocking schemes for high speed digital

- systems,” *IEEE Tans. Comput.*, vol. C-35, no., 10, pp. 880-895, Oct. 1986.
- [6] J.M. Rabey et al., *Digital Integrated Circuits: A design perspective* 2nd edition Prentice Hall of India, 2005.
- [7] *Engineering Design Systems: LSSD Rules and Applications*, manual 3531, IBM, Corp., Armonk, NY, 1985.
- [8] J. U. Nikolic, “Improved sense amplifier based-flip flop: design and Measurements,” *IEEE Trans. Electron Devices*, vol.35 no.6, pp. 35– 39, Jun. 2000.
- [9] H. Mahmoodi, V. Tirumalashetty, M. cooke and kaushik roy, “Ultra low power clocking scheme using energy recovery and clock gating,” *VLSI IEEE Trans.*, vol. 17 no.1, pp. 33–46, Jan. 2009.
- [10] F. Moradi, T. V. Vao, D. Wisland, C. Augstine, A. Goel, G. Karakonstantis, K .Roy, H. Mahmoodi “Data dependent sense amplifier flip flop for low power application,” in *2010 IEEE Int. Conf.*.
- [11] G. M. Strollo, D. D. Caro, E. Napoli and N. Petra “A novel high speed Sense-amplifier based flip flop,” *VLSI IEE Transaction*, vol. 13 no. 11 pp. 1266–1274 Nov. 2005.
- [12] J. Kim, Y. Yang and H. Park, “CMOS sense amplifier based flip flop with two NC²MOS output latches,” *Electron. Lett.* vol. 36 no.6, pp.498-500, Mar. 2000.
- [13] M. Matsui, H. Hara, Y. Uetani, L. Kim, T. Nagamatsu, Y. Watanabe, A.chiba, K. Matsuda and T. sakurai “A 200MHz 13 mm² 2D DCT macrocell using sense amplifying using pipeline flip flop scheme,” *IEEE J. Solid State Circuits*, vol. 29, no. 12, pp 1482-1490, Dec. 1994.
- [14] J. Montanaro et al., “A 160 MHz 32-b 0.5-W CMOS RISC microprocessor,” *IEEE J. Solid State Circuits* vol. 31, no. 11, pp. 1703-1714, Nov 1996 .
- [15] J. Kim, Y. Jang, and H. Park “CMOS sense-amplifier based flip flop with two N-C²MOS output latches,” *Electron. Lett.*, vol.36, no. 6, pp. 498-500, Mar 2000.