Realization of 16 Gbit/s all-optical Toggle memory utilizing change in polarization state of light in single-mode optical fiber*

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In this investigation, all-optical Toggle flip-flop event-driven memory is explored with data rate of 16 Gbit/s. Single mode optical fiber model is used as a nonlinear medium to generate the output set and reset pulses of a Toggle flip-flop, and the model is based on the bidirectional optical transmission principle, considering the fundamental effects of cross phase modulation and self-phase modulation with change in polarization state. The performance of a flip-flop is evaluated using truth table conditions and performance parameters such as Q factor, which is obtained as 380.92 dB for Q and 272.9 dB for $\bar{Q}$, and rising and falling times of 7.304 ps and 5.79 ps, respectively are obtained, which makes flip-flop design fast as compared to earlier design techniques.

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Light is used to transmit messages in optical communication. The optical processing of light signals in general is essential step toward in the future development of fiber optics system of communication. The increasing demand for transmission bandwidth has been driven primarily by the exponential growth of internet traffic[1]. Switching and routing should be done on the physical layer, eliminating optical-to-electrical and electrical-to-optical converters, to increase network efficiency and enable high data bit rates. When compared to their electronic counterparts, all-optical systems have faster processing speeds and more transparent data formats. Recent advances in photonics, optical signal processing, and switching have made it possible to transmit data at speeds of terabits per fiber and gigabits per wavelength. Future optical packet switching networks can use all-optical flip-flop to carry out a range of optical signal processing tasks. Examples of such applications include storing of a packet's header information, fundamental components of regenerative memory systems, threshold operations and self-routing, optical congestion systems, optical shift registers, optical counters, and many others.

Significant research has been conducted in recent years employing all-optical flip-flop as the fundamental components of many photonic solutions. The laser that has been lasing determines the flip-flop condition. It derives the rate equation from steady-state characteristics[2]. The speed of processors has greatly increased in the current computing era, but memory components such electronic latches and flip-flops continue to have slow access and restricted bandwidth, which restricts processor performance. It is crucial to bridge the gap between slow memory devices and fast processors.

Designing ultra-fast optical memory and ultra-high-speed optical latching devices that can deliver bandwidth at extremely high data rates is the focus of recent research[3]. Numerous devices that exhibit optical bi-stability have already been studied. The master-slave flip-flop is based on two lasers that are linked in a ring-like configuration uses the same phenomenon to give switching and buffering capabilities[4]. Numerous other designs are also based on semiconductor optical amplifier-Mach-Zehnder interferometer (SOA-MZI)[5-10]. In the case of distributed feedback (DFB) lasers and vertical cylindrical surface radiating lasers, other methods are also investigated that are based on the modification of the feedback signal[11]. Based on the characteristics of fibers doped with erbium, solutions are also reported[12]. Devices have a slow switching response and a high input control power need for operation[13,14]. The flip-flop concept was based on a laser model that maintained constant carrier density along the laser's length. The system's speed will be determined by the inherent modulation bandwidth of the individual lasers. Correct logic operations of the test circuit, including Toggle flip-flop, at low frequencies because they may function as temporary memory elements, all-optical flip-flops are an important component[15]. But most of these ideas are either very

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expensive or need a difficult active-passive integration. The synchronous S-R flip-flop, which is based on two additional MZI structures and a hybrid integrated S-R latch, has an extinction ratio of 18 dB and switching time of less than 450 ps[16]. High speed all-optical flip-flop operation with 25 ps pulses was obtained based on an asymmetric active multimode interferometer[17]. The Toggle flip-flop design requires the fewest active components and only one toggling signal as input[18]. Utilizing silicon-on-insulator (SOI) technology and integrated short-length feedback-loop solutions, this architecture can attain multi-Gbit/s operational rates. The condition for all-optical flip-flops relying on semiconductor technology will be examined[19], including the optimum outcomes in case of transition time and switching power.

Even if certain strategies have previously been handled, research in the field of optical technology is still in its early phases. Realized Toggle memory design in this research is compact and easy to integrate and requires a smaller number of components, and on the other hand improved results are obtained in terms of bit rate[20-23] quality factor with the use of a bidirectional transmission model. Nonlinear effects cross phase and self-modulation in single mode fiber, together with a change in polarization state, led to achieve reset and set pulses at high bit rate of 16 Gbit/s that resemble Toggle flip-flop output. The functionality of obtained flip-flop Toggle memory model is evaluated using truth table conditions and performance metrics Q factor, which is obtained as 380.92 dB for Q and 272.9 dB for $\bar{Q}$, respectively, rise time and fall time which plays important role in the flip-flop design. The time it takes the flip-flop to travel from low to high or high to low is proportional to its speed. When the rise and fall time increases, the system may become slow and sluggish. Rise time and fall time attained as 7.304 ps and 5.79 ps, which makes flip-flop design efficient for the optical signal transmission applications where large number of flip-flops are connected as compared to earlier flip-flop schemes, where ns-level rise and fall time response is obtained, making the system slow and sluggish.

The Toggle flip-flop is a synchronous device that changes the state of the flip-flop output by passing high to low or low to high transitions through a clock signal as shown in Fig.1. In this model, the Toggle signal is denoted by T, while the output set and reset pulses of the given input signal are denoted by Q and $\bar{Q}$. $\bar{Q}$ is in inversion of Q.

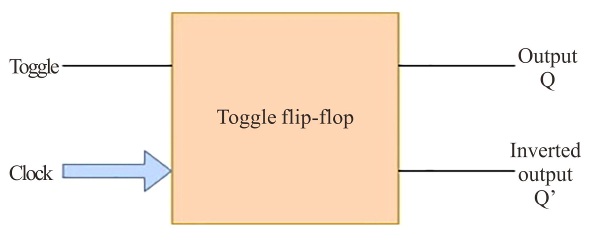

Fig.1 Basic Toggle flip-flop

A Toggle flip-flop has two stable states: 0 and 1. When the T flip-flop's current state is zero, it will remain in that state Q=0 until a high-level signal T=1 is applied. If on the other hand, the flip-flop is in stable condition 1 and input T=0 is applied, the flip-flop will remain in present stable condition as shown in state diagram of Fig.2. Only when the applied input is high, there will there be a transition from this condition to other stable condition, hence the name is Toggle flip-flop.

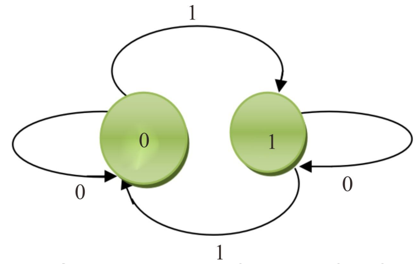

Fig.2 State diagram of Toggle flip-flop

The output toggles when the given input is high, but when the input is low, the output keeps the previous input as shown in Tab.1. Characteristics table in tabular form represent possible output. Q_{n+1} represents the output state of the Toggle flip-flop. The previous state is represented by Q_n, while the applied input to the optical Toggle flip-flop is represented by T. From the combination of present input and past outputs, characteristic is obtained further from this table, and the output state equation Eq.(1) is derived.

Tab.1 Characteristic table of T flip-flop

	Last state		Next state	
T	Q_n	$\bar{Q}_n$	Q_{n+1}	$\bar{Q}_{n+1}$
0	0	1	0	1
0	1	0	1	0
1	0	1	1	0
1	1	0	0	1

The k map shown in Fig.3 can be obtained for Toggle flip-flop. It can be concluded from the characteristic table that the output of Toggle flip-flop goes into the transition to next stable state only when the toggle signal T is high, otherwise it remains in the present stable state. When a high-level signal is introduced, the output will change from 0 to 1.

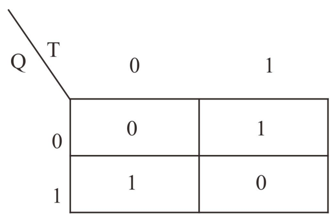

Fig.3 The k map

$$Q_{n+1} = T\overline{Q}_n + \overline{T}_n Q_n. \quad (1)$$

The primary benefits of adopting bidirectional transmission via a single optical fiber versus "two different fibers" are the possible cost savings from an integrated transceiver design as well as the two-fold decrease in infrastructure (fibers, optical splitters, and optical amplifiers). Bidirectional transmission increases costs and makes system design more challenging. A particular optical component is needed for "duplex" systems to receive the bidirectional signals at the transceiver, and crosstalk between the bidirectional signals should be kept to a minimum.

The configuration shown in Fig.4 is utilized to obtain a 16 Gbit/s all-optical Toggle memory signal by transferring the output of a continous-wave laser with wavelength of 1 550 nm and 3 mW power via a Mach-Zehnder modulator, which vary optical wave's amplitude and is driven by the bit sequence generator. A bit sequence generator purpose is to produce a predetermined set of outputs. This binary code is produced by the non-return to zero pulse generator. Ones are represented by one significant state, which is often a positive voltage, and zeros are represented by another significant state, which is typically a negative voltage, with no neutral or rest state in between Mach-Zehnder modulator is employed with extinction ratio of 16 dB. By means of electro-optic effect externally applied voltage can be used to vary the refractive index in the waveguide branch. The different waveguide path can lead to constructive or destructive interference at the output. Output intensity can be modulated according to modulating voltage. Ideal power splitter divides the modulated wave output into two equal ratios of 50: 50. The equal separated signals are then fed into two separate channels. Time delay of 9×10^{-11} s is introduced in the upper channel to obtain the required truth table results. In each channel erbium-doped fiber amplifier (EDFA) is introduced to raise the intensity of the optical signals with various parameters listed in Tab.2. Forward pump power is set as 20 dB/m while forward pump wavelength and backward pump wavelength is taken as 980 nm. Output from two EDFA modules is transmitted to polarization controllers. Polarization controller is a device used in each arm to control the polarization state of light. Through this device, it is possible to regulate the polarization of light inside fibers.

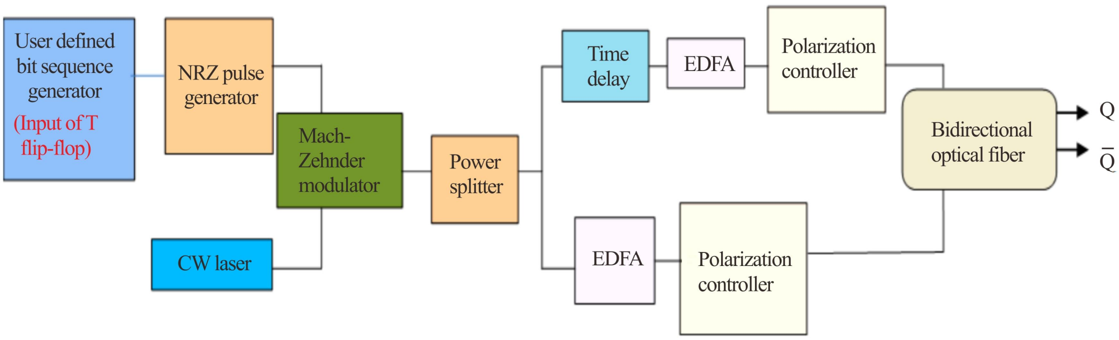

Fig.4 Simulation setup of all-optical Toggle flip-flop

A technique analogous to the system of latitude and longitude used to find places on the earth's globe is employed to map polarization states to the Poincare sphere. Two angular variables (ellipticity and azimuth) and a radius are used to specify the coordinates of places both outside and inside the Poincare sphere. The spherical model has the important advantage of simplifying the computations required to compute incremental changes in polarization state. Linear states (L) occupy the equator in Poincare sphere while right (RCP) and left circular polarization (LCP) states are at the north and south poles. Elliptically polarized state is represented on the surface of Poincare sphere. Each state of polarization is represented by unique point on the sphere. The azimuth and ellipticity parameter define the polarization state of the output signal. Value of azimuth lies between −90° and 90°, while the ellipticity lies between −45° and 45°, as shown in Fig.5. The polarization value for upper channel is adjusted with the azimuth value of 0.005 34° and ellipticity value of −0.000 04° as shown in Poincare sphere in Fig.6 respectively. For the lower channel, the respective values are set at 0.001 93° and −0.012 53° as shown in Fig.7. Polarization states are characterized by polarization state's azimuth angle and elliptical angle, the polarized output signal is from the two channels are guided through the bidirectional optical fiber with a length of 0.5 km. This component provides functionality of total field approach with bidirectional propagation of optical signal in single mode fiber.

Non-linear Kerr effects taken in this model are self-phase modulation, cross phase modulation along with Brillouin scattering and Raman scattering, making field model more accurate. At the output, two signals are obtained Q and $\overline{Q}$ from the bidirectional optical amplifier. Due to the influence of nonlinearities self-phase modulation, cross phase modulation, Brillouin scattering, and Raman scattering model, constructive or destructive pulses are obtained from the bidirectional fiber transmission, which are optimized to match the state of Toggle memory truth table at high data rate of 16 Gbit/s. At the data rate of 16 Gbit/s, input signals sequences 10101010 and 01010101 are provided to the simulation setup as shown in Fig.4. The nonlinearity inside optical fiber is raised in order to match the output with the truth table of the Toggle flip-flop considering self-phase and cross phase modulation effect. Consider the case when this input sequence of 10101010 is provided to the Mach-Zehnder modulator via a user-defined bit sequence generator as shown in Fig.8 along with a pump signal of 1 550 nm, and the output is further split into two equal parts with proper delay adjustment. The signal is appropriately polarized before it is sent through single mode bidirectional transmission optical fiber. When a binary high signal is sent into the circuit, it toggles and generates a low output of 01010101.

Tab.2 Simulation parameters of EDFA amplifier

Parameter	Value	Unit
Core radius	2.2	μm
Er doping radius	2.2	μm
Er metastable lifetime	10	ms
Numerical aperture	0.24	m^{-3}
Er ion density	10^{25}	
Loss at 1 550 nm	0.1	dB/m
Loss at 980 nm	0.15	dB/m
Length of EDFA amplifier	6	m
Forward pump power	20	dBm
Backward pump power	0	mW
Forward pump wavelength	980	nm
Backward pump wavelength	980	nm

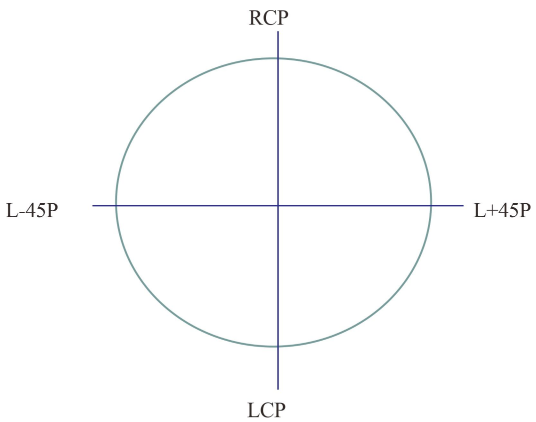

Fig.5 Basics of Poincare square

When a low voltage signal is used as an input, the output is high; indicating that the previous state input was stored. Corresponding output sequences Q and $\overline{Q}$ are obtained as shown in Fig.9 and Fig.10. Like this condition when the input sequence is 01010101 as shown in Fig.11, Q output obtained is 10101010. On the other hand, $\overline{Q}$ output is reverse of Q, and 01010101 is obtained, thus matching the truth table condition of Toggle flip-flop as shown in Fig.12 and Fig.13, and by investigating these results, it is concluded that when the Toggle input signal is high, there will be change in the output to next stable state, but when input is low, the previous bit value is stored. Thus, the output matches the truth table condition of Toggle flip-flop. Self-phase modulation, cross phase modulation along with light polarization in bidirectional transmission led to achieving Toggle memory at high bit rate, and further EDFA in the setup improves the signal quality.

The *Q*-factor simplifies the examination of data performance of the system[24]. The simplest straightforward indicator of the bit error rate (*BER*) is a measure of system performance, although the computation of the *BER* necessitates a complete examination integral of normal distribution. Since the introduction of this integral, there is no closed-form solution, and this assessment requires the use of numerical integration of the design or tabular values. In this investigation, quality factor of 380.92 dB is obtained for Q output signal, while for $\overline{Q}$ signal output, 272.9 dB is obtained. Acceptable performance outcomes are obtained in the Toggle flip-flop as shown in Fig.14 and Fig.15.

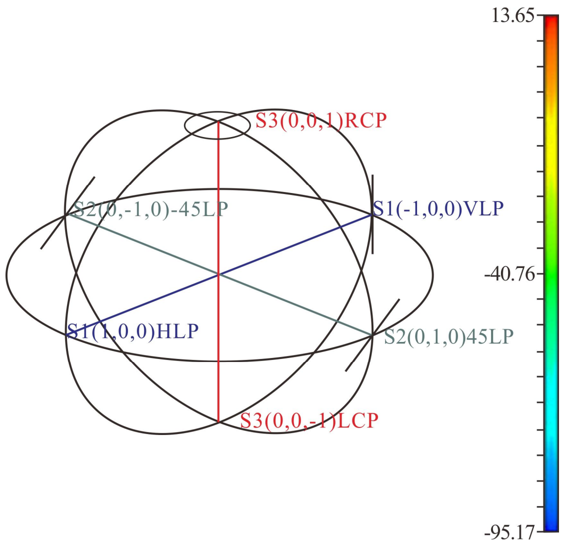

Fig.6 Azimuth and ellipticity values of 0.005 34° and −0.000 04°

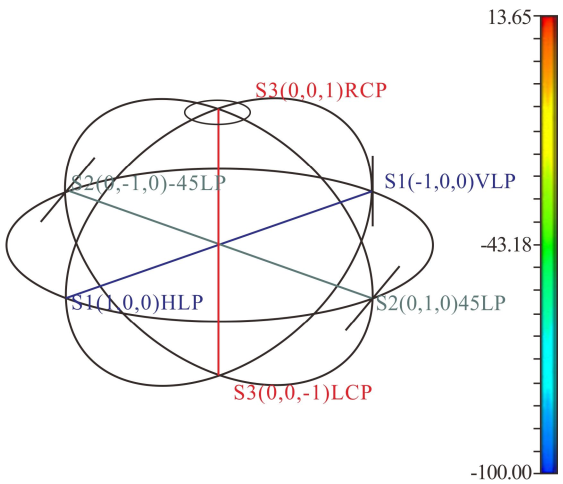

Fig.7 Azimuth and ellipticity values of 0.001 93° and −0.012 53°

One of the primary parameters on which flip-flops may be assessed is speed. The time it takes the flip-flop to move from low to high or high to low condition is directly related to its speed. A huge number of flip-flops are used in high-speed optical processing networks. The increasing of the amount of rise and fall time may cause the system to become slow and sluggish. The speed of a flip-flop is determined by the rising and fall time. Complications with the duty cycle of the clock signal will emerge, if the rise time and fall time are not aligned. The rise time and fall time of the Toggle flip-flop are the time it takes to change state from 0 to 1 or 1 to 0, and are measured at 10% and 90%, respectively[25].

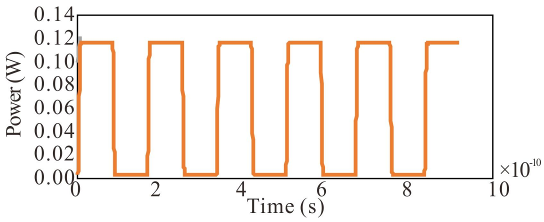

Fig.8 Input to Toggle flip-flop 10101010

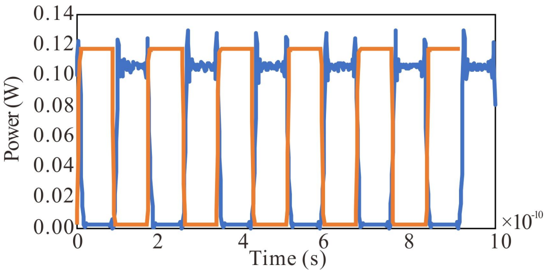

Fig.9 Q output signal obtained from Toggle flip-flop at 16 Gbit/s 01010101

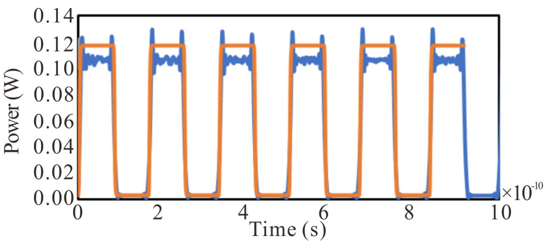

Fig.10 $\bar{Q}$ output signal obtained from Toggle flip-flop at 16 Gbit/s 10101010

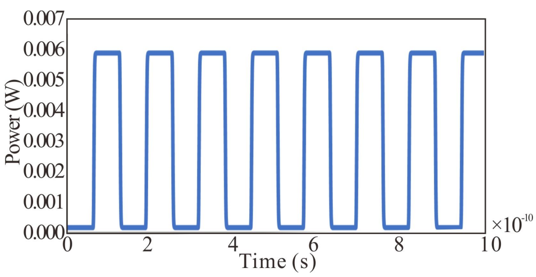

Fig.11 Input to Toggle flip-flop 01010101

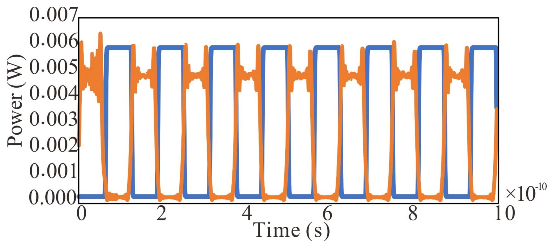

Fig.12 Q output signal obtained from Toggle flip-flop at 16 Gbit/s 10101010

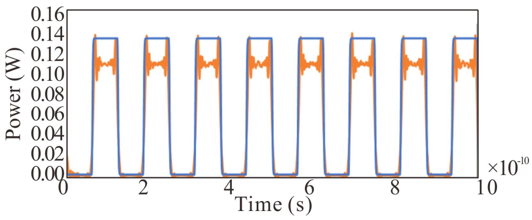

Fig.13 $\bar{Q}$ output signal obtained from Toggle flip-flop at 16 Gbit/s 01010101

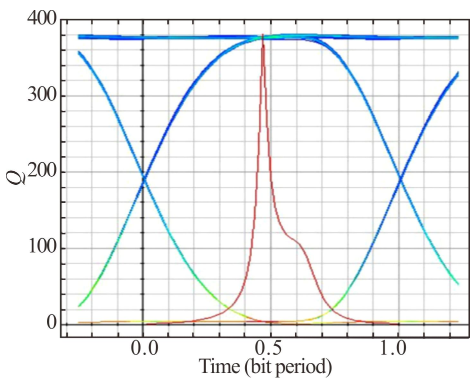

Fig.14 Eye diagram of Q signal of optical Toggle flip-flop with Toggle quality factor of 380.92 dB

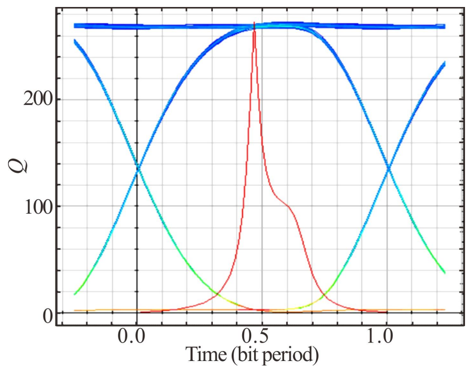

Fig.15 Eye diagram of Q signal of optical Toggle flip-flop with Toggle quality factor of 272.9 dB

Because the resulting system has the potential to reach a meta stable state, it is crucial to focus on, which indicates that obtained T optical memory function fast than electrical RAM time constraints. In this experiment, the rise and fall periods were measured to be 7.304 ps and 5.79 ps, respectively as shown in Fig.16 and Fig.17. Further, this memory setup is simple and economical with high bit rate of 16 Gbit/s and can be easily used for packet transmission for storing and toggling the inputs bit.

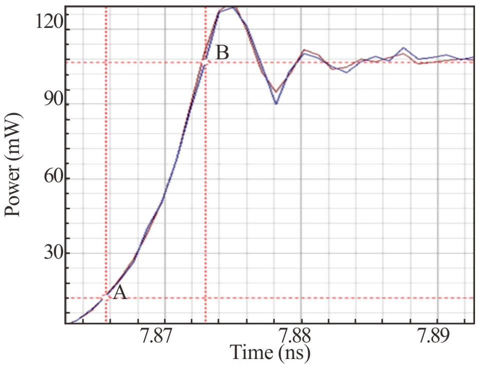

Fig.16 Rise time of 7.304 ps

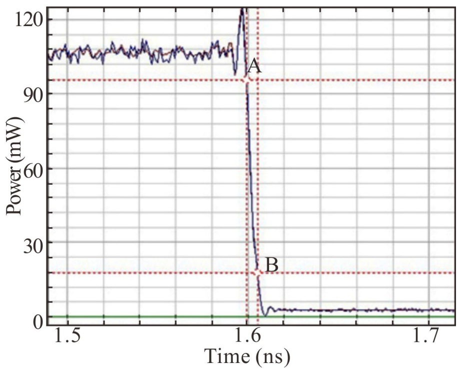

Fig.17 Fall time of 5.79 ps

Optisim 7 software is used to simulate the all-optical Toggle flip-flop memory with a bit rate of 16 Gbit/s using bidirectional transmission model in a single mode optical fiber. Cross phase modulation and self-phase modulation nonlinear phenomena are amplified in the single mode optical fiber, which is employed to create the output set and reset pulses for optical Toggle flip-flop memory, along with the change in light polarization. The proposed technology can run at many gigabits per second. This design achieves a higher bit rate of 16 Gbit/s while maintaining a very high-quality factor and with a much smaller rise time and fall time in the range of ps as compared to previous designs.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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