Design of polarization switch in a single micro-ring resonator and its application to design all-optical logic OR/NOR gates using FDTD

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***Abstract*—The present paper explain the demonstration of all-optical polarization switch in a single silicon micro-ring resonator also called optical ring resonator (ORR) with the application of suitable and optimized nature of polarized light as a pump pulse. The conversion of polarization states occur in the outputs of ORR. The "polarization-conversion" behavior with respect to change in nature of pump signal in the ORR is used to achieve various all-optical logic circuits. The projected optical switch is used to implement all-optical OR / NOR gate, in through port (TP) and drop port (DP)of the ORR simultaneously. The switching action with respect to time is reported in the article, to justify its behavior of an "all-optical switch". The proposed architecture may be employed to implement other polarization-conversion dependent logic and arithmetic circuits. The results obtained from FDTD simulations verified the proposed method. Some 'figure of merits' are calculated and also discussed in the report to highlight its advantages.**

Keywords—all-optical logic circuit, all-optical switch(AOS), FDTD model, optical-ring resonator, polarization switch.

I. INTRODUCTION

Recently, silicon-based devices have shown potential in photonics due to its capability to fabricate in micro level. Due to its low cost, high bandwidth as well as excellent integration capability, it has attracted much interest. Silicon has been studied in [1], which shows its several advantages for use in the optical domain.

In recent years, many researchers proposed polarization conversion in optical domain and present its application in optical switching. Mach-Zehnder interferometer (MZI) is very use-full in optical fiber domain. MZI combined with optical fiber to design polarization dependent (AOS). Polarization-dependsORR can be simulate (AOS) by operating the polarization characteristics' of the light wave. Mode-conversion in silicon micro-ring resonators are already presented in [2, 3].

Various optical logic gates perform major role in very highspeed signal processing, fast information processing, and efficient computing. Large number of researchers designed different ORR based logical gates like AND,OR, NAND, etc, by employing different optical devices such as terahertz optical asymmetric de-multiplexer (TOAD), ORR, etc [3]-[4]. Among all-opticaldevices, ORR is more advantageous than others based on ultra-compactness, require small amount of power and fast switching speed. Because of the uniqueness of the silicon based ORR, it can be exploited to make optical switches, optical filters, logic shifters, multiplexer/de-multiplexer, all-optical logic gates, converters, etc [5]-[6].

In the report, we developed a new approach for designing AOS and designing of all-optical OR and NOR logic gates based on the polarization state of input and output states in a silicon based optical-ring resonator ('ORR'). The main advantage of this model is that only a single ORR can perform both the logic operations. It is capable to allow both the quasi-TE and quasi-TM mode, unlike in the situation of [7]. The quasi-TE mode represents "1" or "High" state while quasi-TM denotes"0" or "Low" state. This proposed structure has ability to realizing complex logic functions by cascading of two ORR or more than two ORR.

The paper is divided into six parts: the polarization conversion based optical switching of the optical-ring resonator (ORR) is explained in part-II. Part -III explains the concept and design of the structure, part-IV highlights simulated results and section-V presents explanation of the paper and finally part-VI concludes the paper.

II. THEORY OF 'AOS'USING POLARIZATION-CONVERSIONIN ORR

Fig. 1 indicates the race-track ORR with two straight waveguides which is used to find the polarization conversion. The source signal combine with pump signal applied from the input terminal in the proposed ORR. The outputs are analyzed by TP and DP. The conversion of polarization takes place in the TP and DP of the ORR due to the use of appropriate nature of pump power. When High"Logic-1"or Low "Logic-0"modeof light having suitable wavelength passes through the input port, then one of the resonant-wavelengths coupled into the ORR and it appears at DP on resonance. The other mode of light that is not interacts to the optical ring waveguide at TP. Also, due to pump pulse, changes in refractive index and an 180^0 difference of phase is attained in a full cycle of the ORR waveguide. The phenomena of switching occur at TP and DP. In this paper, both output ports are utilized to design

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OR/NOR logic gates simultaneously. The various parameters used to design are listed below in Table I.

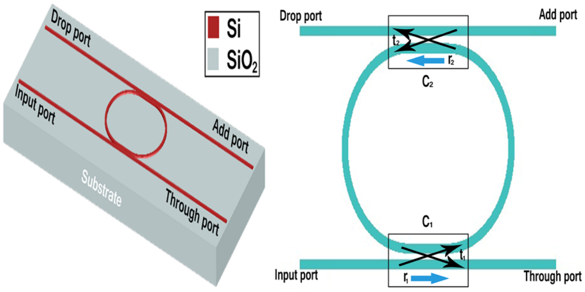

Fig. 1(a).Schematic of MRR (b).Schematic of race-track MRR

TABLE I LIST OF SPECIFICATION FOR DESIGN THE SYSTEM

S. No.	Specification	Characterization
1.	Substrate components	SiO_2 (Glass)
2.	ORRcomponents	Si
3.	Bending radius of ORR	5µm
4.	Ring wavelength gap in straight guide	0.1µm
5.	Coupling length (L_c)	3µm
6.	Coupling coefficient (r, t)	0.837, 0.547
7.	Waveguide height (h_g)	0.18µm
8.	Waveguide width (w_g)	0.4µm
9.	Attenuation losses (α) of the ring	Around 10dB/cm

The ring resonator transfer function for polarization conversion from TE-TE (H_{EE}) or TM-TM (H_{MM}) and TE-TM (H_{EM}) or TM-TE (H_{ME}) at TP and DP are derived using Fig 1(b).

Eq. (1) and Eq. (2) represents the polarization conversion based transfer function at through port of micro-ring resonator [8].

$$H_{TEEor\ TMM} = \frac{r_1 + \gamma[-r_2\cos(\emptyset)(1+r_1^2) \pm jt_1^2 r_2 R\sin(\emptyset)]z^{-1} + \gamma r_1 r_2^2 z^{-2}}{1+\gamma^2 r_1^2 r_2^2 z^{-2} - 2\gamma r_1 r_2 z^{-1}\cos(\emptyset)} \quad (1)$$

$$H_{TEM\ or\ TME} = \frac{j\gamma t_1^2 r_2 S z^{-1}\sin(\emptyset)}{1+\gamma^2 r_1^2 r_2^2 z^{-2} - 2\gamma r_1 r_2 z^{-1}\cos(\emptyset)} \quad (2)$$

Similarly, the polarization-based transfer function at drop port is given below in (3) and (4) [8].

$$H_{DEEor\ DMM} = \frac{\gamma^{\frac{-1}{2}} t_1 t_2 z^{\frac{-1}{2}}\{r_1 r_2[\cos\left(\emptyset/2\right) \pm jR\sin(\emptyset/2)] + \gamma[\cos\left(\emptyset/2\right) \pm jR\sin\left(\emptyset/2\right)]\}z^{-1}}{1+\gamma^2 r_1^2 r_2^2 z^{-2} - 2\gamma r_1 r_2 z^{-1}\cos(\emptyset)} \quad (3)$$

$$H_{DEMor\ DME} = \frac{jt_1 t_2 S\sin\left(\emptyset/2\right) z^{-(1/2)}(r_1 r_2 + z^{-1})}{1+\gamma^2 r_1^2 r_2^2 z^{-2} - 2\gamma r_1 r_2 z^{-1}\cos(\emptyset)} \quad (4)$$

Where $\pm$ sign indicate the $H_{TEE\ or\ TMM}$ and $H_{DEE\ or\ DMM}$. And $z^{-1} = e^{-j\beta L}$ where L representlength of (ORR) coupling length of the ring, r_1 and $r_2$represents self-coupling coefficients of the coupler and t_1 and t_2 are the cross-coupling coefficient of the coupler 1 (C_1) and coupler 2 (C_2) of the ring respectively. $\beta = (\beta_{TM} + \beta_{TE})/2$ represent mean of the phase parameter of the both modes, $R = \frac{\Delta\beta}{2\delta}$, $S^2 = 1 - R^2$, $\Delta\beta = \beta_{TE} - \beta_{TM}$, $\emptyset = \delta L$, $\delta = (\frac{\Delta\beta}{4} + K_P^2)^{1/2}$, $K_P = S^2\sin^2\emptyset$ is the coefficient of coupling power between the two modes and γ represents the total losses occurs in the ring.

Eq. (1) to Eq. (4) represents polarization conversion based MRR.

III. Design of All-Optical OR/NOR Logical gatesusing Polarization Switchin a ORR

In the proposed structure of polarization based switch, a fixed source of polarized light at "Logic-1" is applied and the state of polarization of various pump power (P_1) is provided from the same input port (IP). Depending on the nature of pump (P_1) signal, the different nature of outputs is obtained from TP and DP. And for demonstration of optical logic "OR/NOR" gates, two pump signals (P_1 and P_2) and a fixed light source of High ("Logic-1") nature are inserted through the input port simultaneously. We can altered the pump signal in accordance to the optical OR/ NOR gate, which are obtained at TP and DP of the ORR at the same working frequency.

A MRR is an optical switch which performs optical switching which occurs at TP and DP, due to the application of pump power. Due to pump power, change in refractive-index occurs and consequently all-optical switching achieved between both output ports. When ORR is at the time resonance, DP shows highest transmittance and TP shows least transmittance. While at non resonance condition, TP shows highest transmittance-power and DP shows low transmittance-power. Fig. 2 represents the transmission characteristics of source in the wavelength range [1.52 - 1.555] µm. From Fig. 2, the resonance and non-resonant wavelengths1.53 µm, 1.522µm, and 1.552µm are used as source and pump wavelengths respectively. The all-optical switching action and the logic gates are attained at the working wavelength of 1.53 µm.

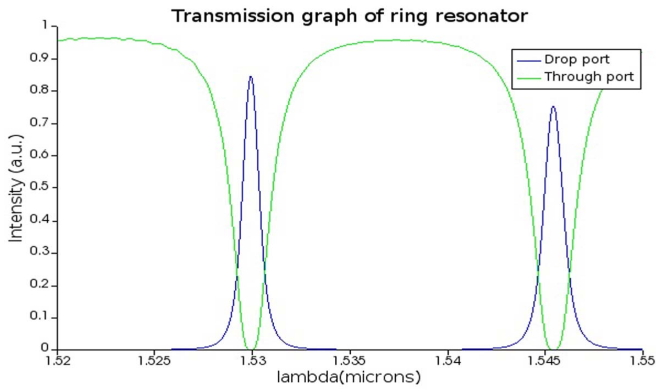

Fig. 2. Transmittance graph of the ORR

In this report, the field intensity at output is used to find nature of output pulse. The high amplitude of output electric field corresponds to High ("Logic-1") polarized state, while the small amplitude of electric field corresponds Low ("Logic-0") polarization state. Fig. 3 shows the proposed design and Eq.(1) to Eq.(4) are utilized for the conversion of polarized states and all-optical logic gates in the ORR.

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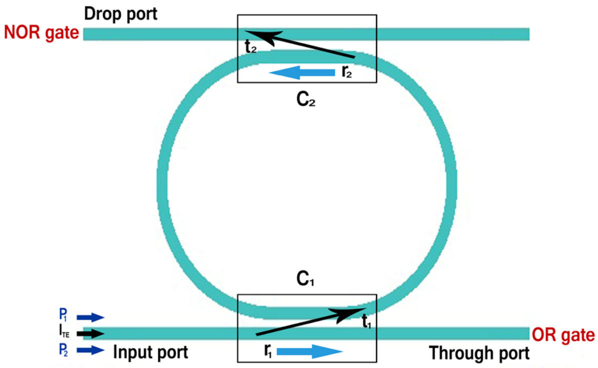

Fig. 3. WorkingSchematicof race-track ring resonator

IV. Simulation Outputs

A. *All-optical polarizationswitching*

In the paper a race-track MRR of suitable bending radius, coupling length and the proper height-to-width (HW) ratio of the waveguide is considered.

The AOS is analyzed with a fixed source (I_{TE}) of High level ("Logic-1") at 1.53 µm and pump signal (P_1) at 1.552µm using FDTD simulation [9]. If the polarization state of both source and pump are High ("Logic-1"), the output of High ("Logic-1") is achieved at TP and Low ("Logic-0") is achieved at DP as shown in Fig. 4(a). Similarly, for the same input of "Logic-1",if the pump signal of "Logic-0" is applied at the wavelength of 1.552µm, Low ("Logic-0") output is occur at TP and High ("Logic-1") output is occur at DP which is shown in Fig. 4(b). The above characteristics resemble conversion in polarization based AOS in ORR. The simulated results are shown in Table II.

TABLE II LIST OF SPECIFICATION FOR POLARIZATION-CONVERSION

Source nature	Pump (P_1) signal	TP-nature	DP-nature
"1"	"1"	" 1"	"0"
"1"	"0"	"0"	"1"

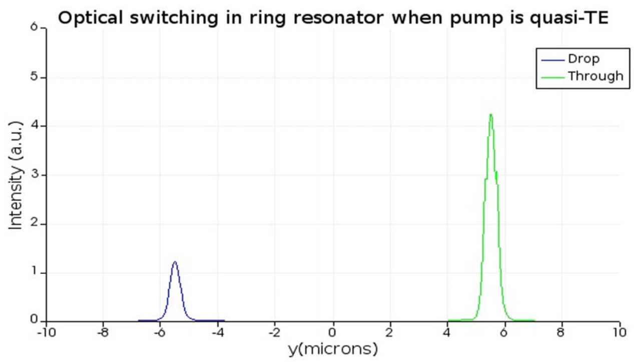

Fig. 4 (a). DP is "Logic 0" and TPis"Logic1"obtained at ORR

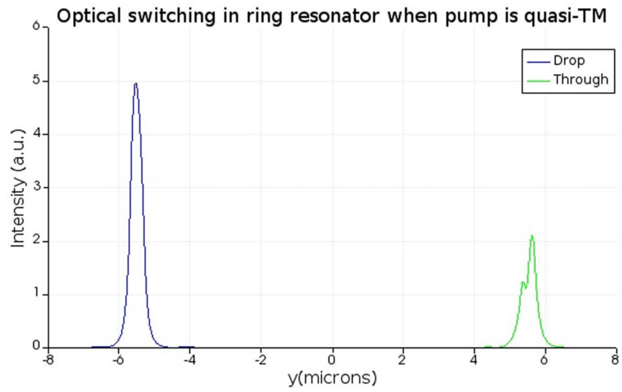

Fig. 4 (b).DP is "Logic 1" and TP is "Logic 0" obtained at ORR

When the applied pump (P_1) of High ("Logic-1") is provided, the TP output shows high field intensity or High ("Logic-1") nature,while DP shows small field intensity Low ("Logic-0"). When the pump (P_1) changes to Low ("Logic-0") nature, the intensity atTP terminal is Low ("Logic-0"), while the intensity of DP is High ("Logic-1"). This phenomena denotes the "all-optical switching" in ORR.

Fig. 5 and Fig. 6,obtained from FDTD simulation,explains the "polarization-conversion basedall-optical switch" in time domain.

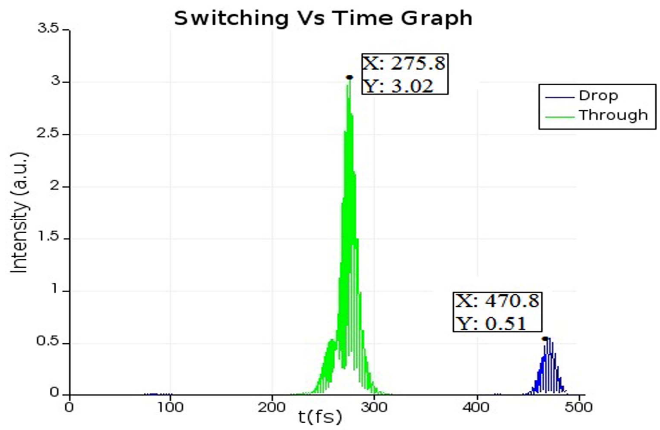

Fig. 5 Switching nature of ORR when applied pump is"Logic-1"

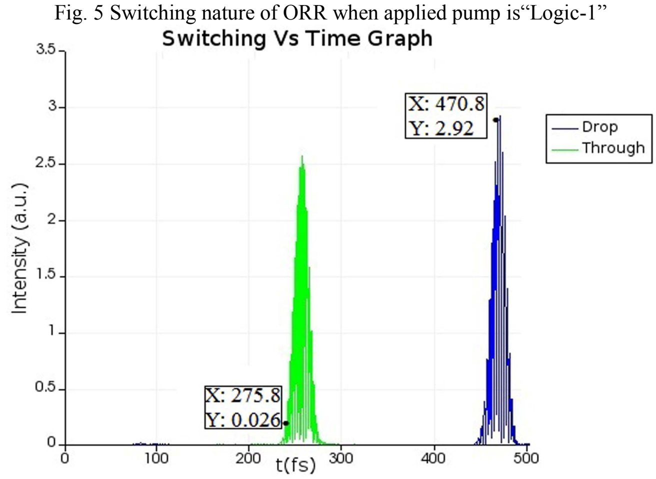

Fig. 6 Switching nature of ORRwhen applied pump is"Logic-0"

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B. *All-optical OR/NOR logic gates*

The OR/NOR gate is achieved if the specified input source (I_{TE}) of High (“Logic-1”)applied at the specific wavelength of 1.53µm and pump supply (P_1,P_2) of 1.522µm and 1.552µmwavelength given to input terminal, as shown in Fig. 3. The conversion of polarization dependent optical OR/NOR logic gates are obtained at TP and DP of the MRR at a wavelength of 1.53µm. If the polarization state of both pumps are High (“Logic-1”), the output of High (“Logic 1”) is attained at TP and Low (“Logic-0”) is observed at DP as shown in Fig. 7(a) and Fig. 8(a) respectively. If either pump (P_1 or P_2) of High (“logic-1”) or Low (“logic-0”) signal is injected, the output of High (“logic-1”) is attained at TP as shown in Fig. 7(b) and Fig. 7(c) respectively. Moreover, Low (“logic-0”) is obtained at DP output which is shown in Fig. 8(b) and Fig. 8(c) respectively. But, if we select the state of polarization of both the pumps P_1 and P_2 as Low (“logic-0”), the output of Low (“Logic-0”) and High (“Logic-1”) is obtained at TP and DP respectively, which is demonstrated in Fig. 7(d) and Fig. 8(d) respectively. The state of outputs indicates the optical OR/NOR logic gates as shown in Table III.

TABLE III POLARIZATION-CONVERSION BASED ALL-OPTICAL SWITCH IN ORR

Source nature	Pump (P_1) signal	Pump (P_2) signal	TP-OR Gate	DP-NOR Gate
“1”	“1”	“1”	“1”	“0”
“1”	“1”	“0”	“1”	“0”
“1”	“0”	“1”	“1”	“0”
“1”	“0”	“0”	“0”	“1”

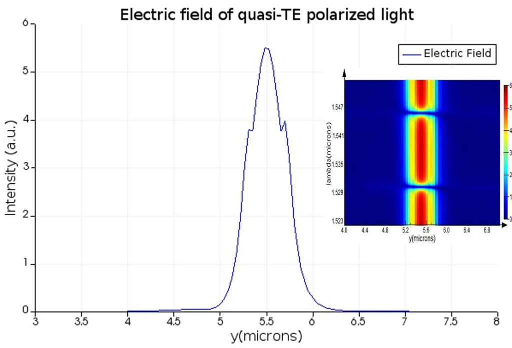

Fig. 7(a).Output: High if both pumps are “Logic 1”

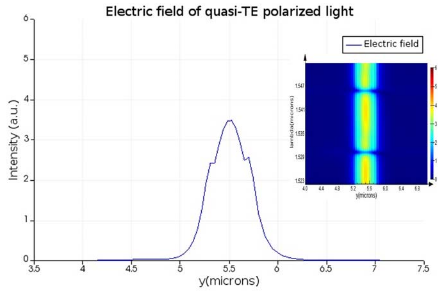

Fig. 7(b).Output: High if pumps are “Logic 1” and Logic 0”

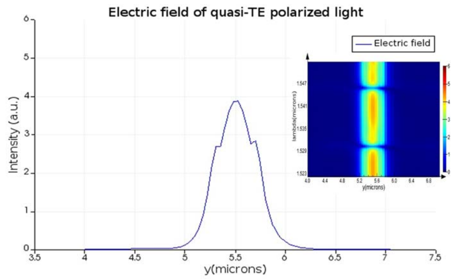

Fig.7(c).Output: High if pumps are “Logic 0” and “Logic 1”

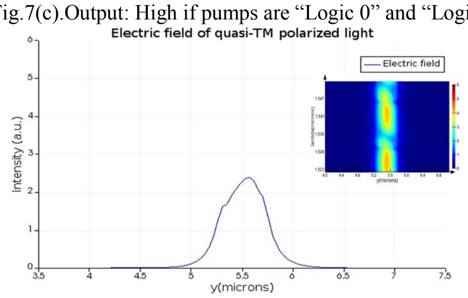

Fig. 7(d).Output: Low if both pumps are “Logic 0”

Fig. 7. Output fields occur at TP (OR Logic Gate)

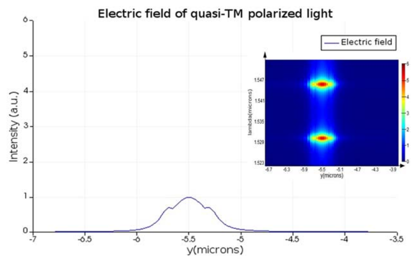

Fig. 8(a).Output: Low if both pums are “Logic -1”

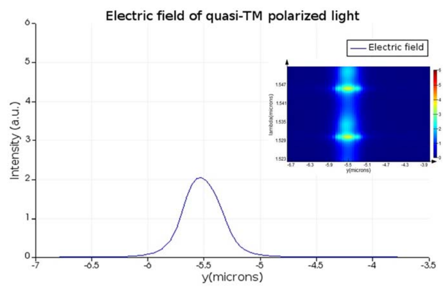

Fig. 8(b). Output: Low if pumps are “Logic 1” and “Logic 0”

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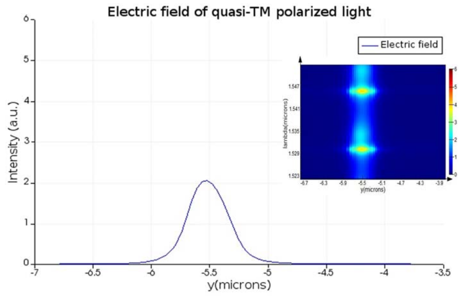

Fig. 8(c). Output: Low if pumps are "Logic 0" and "Logic 1"

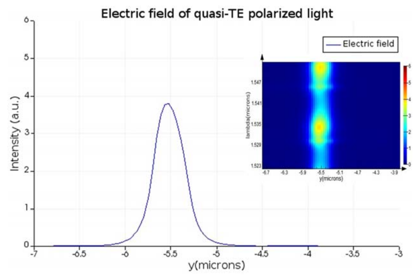

Fig. 8 (d).Output: High if both pumps are "Logic 0"

Fig. 8.Outputs field chart obtain at DP (NOR Logic Gate)

V. Discussions

To validate the proposed scheme, we examine and calculate different figure of merits (FOM).

a). Operational Speed-The output polarized lights are showing on and off state or switching characteristics by regulating pump signals[10].

The delay time for TP as well as DP is about 0.2 ps for both optical switching and optical OR/NOR logic gates, as obtained from simulation.

b). Quality factor is useful in determining the spectral range of ORR. Large cavity length can lead to a high value of Q-factor. But, the overall propagation loss increases with the increase in the cavity length. Thus, an optimization has to be performed to get the high Q-factor [10].

VI. Conclusions

In the proposed model AOS in the single ORR is realized. Also, the polarization-conversion phenomenon is further extended to implement optical OR and NOR logic gates simultaneously. FDTD simulation results validate the proposed model. The Q-factor is also high around 1400 and 2400 for AOS and optical logic gates in the ORR. The proposed structure can be utilized in future arithmetic and logical circuits. It may also be used in optical computing, optical time-division multiplexing (OTDM) and in optical communication networks.

Acknowledgment

This research work is a part of research project entitled "Polarization conversion and rotation using micro-ring resonator and its application to design binary and multi-valued logic circuits in all optical domain" under taken by Dr. Jayanta Kumar Rakshit which is funded by "Science and Engineering Research Board (SERB) of DST", Govt. of India (Ref. No.: EMR/2017/001324).

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