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The Effect of Oblique Waveguide on All-Optical Photonic Crystal Logic Gates

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Abstract: *All-optical NOT logic gate in the basis of the oblique photonic waveguide structure has been proposed in this paper. The structure of Photonic crystal lattice is triangular and it is formed of dielectric rods in air substrate. The simulation is done using oblique and crossover waveguide structures and a scatter rod in this design. The location of the scatter rod has been selected such a way that the logic gate act as a NOT function in both directions of the structure. The simulated required power consumption becomes200mw for operation of the logic gate. Waveguide bend was used to increase transmission optical power in the proposed scheme and the nonlinear rods were not used which lead to a reduction in the power consumption of the logic gate. Switching time is simulated 0.51ps and extinction ratio of this logic gate becomes9.6 dB. Calculation methods were based on the FDTD and PWE methods.*

Keywords: *All-optical logic gate, photonic crystals, Photonic band gap, bend waveguide, Scatter rod*

1. INTRODUCTION

All-optical NOT logic gate is a basic element in all-optical signal processing and optical telecommunication systems. This logic gate is used to increase processing speed and data transmission [1]. All-optical logic gates based on fiber have difficulty in chip scale integration, and optical logic gates based on waveguide interferometers have a complicated structural arrangement. Moreover, the performance of logic gates with a micro resonator structure and semiconductor optical amplifiers are limited to moment emission noise [2]. Photonic crystals (PC) are a new class of dielectric materials proposed by Yablonovitch and John which can be used in making photonic integration devices with dimensions equal to a wavelength [3]. Presence of photonic crystals (PC) in the design of all-optical logic gates leads to a high potential in compression and reduction of the size of ultra-fast switching devices as well as reduction in power consumption [4].Photonic crystals transmit or reflect light selectively at different wavelengths. There is a period of wavelength which reflects light totally due to scatterings in the crystal lattice and it is called photonic band gap[5]. Forming a defect in the structure of the crystal lattice, light will transmit in the band gap range. A defect is created by removing a row of rods in the crystal lattice structure and is called waveguide [5]. Jiang et al (2010) suggested all-optical photonic crystal NOT logic gate in which two straight waveguides and one photonic resonator located between two waveguides were used to form logic gates. The resonator is placed with a 45 degree angle among waveguides which led to a destructive interference in some frequencies and made passing operations difficult. Amount of passing power was reported %17 in low state and %85 in high state [6]. Nous had et al (2011) proposed a design of two all-optical photonic logic gates; one of them was NOT gate. Photonic straight waveguides were used in a crossover form in this structure. One non-linear rod with a larger radius comparing to other rods was used which lead to increase in the power consumption of the gate. The power transmission in logic gate output was reported %90 in the active mode [7]. Rani Prety et al (2013) suggested another design of all-optical logic gate. In this design, structure of a photonic crystal with a triangular lattice of air holes has been used in the substrate dielectric material and a Y-shape wave guide has been used in the structure to achieve logic gates. One hole with a different radius was made in the center of the waveguide. This structure is totally linear. The proposed rate of clarifying the gate extinction ratio became 6dB. This gate operates in a 0.83TBit/s[8]. Achary (2015) proposed a novel scheme for implementation of all-optical logic gate based on 2D photonic crystal structure (PCS). The structure is a simple geometric in its dimension with clear operating principle, it is potentially applicable for photonic integrated circuits. A NOT Gate is realized with the control signal. An important advantage of the proposed class of optical logic gates is also associated with the possibility of performing different logic operations with the same structure by changing the power densities of logic Gates [9]. Ashkan PASHAMEHR et al(2015) used a basic structure of photonic crystal ring resonators and designed all optical logic gates which are working using the Kerr effect. The proposed gates consisted of upper and lower waveguides coupled through a resonator which was designed for dropping of special wavelength. The all optical gates are designed and the results show that the proposed structures require lower input power for operation [10]. Brahm Raj Singh and Swati Rawal(2015) suggested The designed structure has a hexagonal arrangement of silicon rods in air substrate. They have plotted the transmission, extinction ratio(ER), and tolerance analysis graphs for the structure, and it has been observed that the maximum output is obtained for a telecom wavelength of 1.554 µm. The ER has also been taken into consideration while doing the analysis and is found to be nearly 10 dB for the optical NOT gate designed [11]. Zahra. M et al(2015) We have proposed the all optical XOR, XNOR, NAND and NOT logic gates based on two-dimensional (2D) photonic crystals (PCs).In all structures the nonlinear Kerr effect has been used. Due to the maximum required input power of P_0= 277 (mW/ µ m^2) for the XOR, NOT, and XNOR gates and P_0= 554 (mW/ µ m^2) for the NAND gates, and the high contrast ratio of at least 20 dB between the ON and OFF states, these logic gates are applicable for real time communications[12].Man Mohan Gupta and Sarang Medhekar(2015) are simulated Counter propagating beams (inputs) through nonlinear Mach–Zehnder interferometer (NMZI) with Kerr type nonlinearity and made of photonic crystal waveguides (PCW). Counter propagating inputs ensure "purity" of the output, i.e., output is never a mixture of the input beams. A pure output could be used as input to drive further stages of logic. Possibility of NOT and AND logic allows for the universal NAND logic, and hence, the Boolean completeness[13].In the design of this article, an oblique waveguide is used in such a way that consumption power is reduced and extinction ratio is increased without using nonlinear effects. Suggested logic gate switching time is less than the above mentioned articles.

2. Numerical Analysis Methods

Two steps are used toanalyzethe devices based on photonic crystals. First, plane wave expansion (PWE) method is used to determine band diagram of photonic crystal lattice in order to determine the frequency range of logic gate operation. Second, finite difference time domain method (FDTD) is used to determine transmission amplitude and reflection of optical power in the structure of all-optical logic gates photonic lattice.

3. Analysis of the Structure of Oblique Waveguide and Bend Waveguide

In this section, we analyze the structures of the waveguide. The used structure in the design of suggested optical logic gate is a triangular crystal lattice with dielectric rods in air. An oblique waveguide structure issued in the suggested triangular lattice because of localizing wave vectors along the waveguide which will lead to maximum output signal.

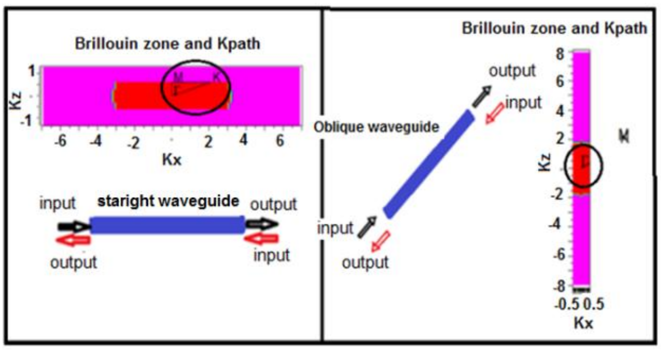

Fig1. *Straight and oblique waveguide structure together with Brillouin zone*

In the suggested structure, radius of the rods is 0.2a, refractive index is 3.4, lattice constant is a=0.609µm and the lattice area is 25*25a^2. In this design, a scattering rod is used for fulfilling logic function. Figure2 shows structure, Brillouin zone and band diagram. Structure band diagram is simulated using PWE method and photonic band gap of the structure is 0.4497-0.2789 (a/λ).

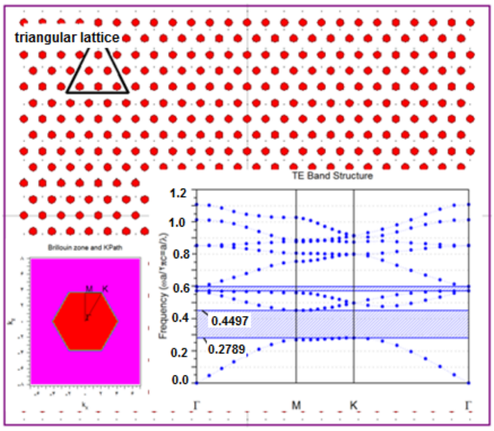

Fig2. *Structure bar diagram of a triangular lattice. Insets show brillo in zone and band structure.*

Now, we create a waveguide in the direction of the M-K by removing a row of rods in the structure. Fig. 3 shows results of band structure for this case. It shows that the band gap of perfect structure is reduced and there is a range of frequcy that wave can be transmitted inside waveguide. According to figure 3, the operating bandwidth for waveguide is about 87.2 nm

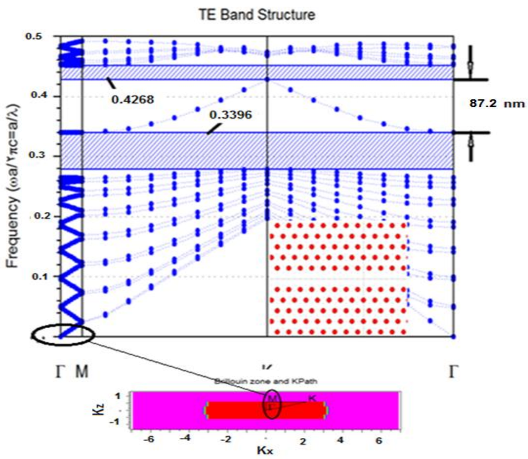

Fig3. *Straight waveguide band diagram as well as Brillouin zone*

A pulse signal with an intermediate frequency is enterd into the waveguide. With emitting pulse inside the waveguide, the amplitude of the transmitted optical power and suitable frequency area for the appropriate operation of the suggested logic gate will be investigated.Figure4 shows the simulated optical power transmission for the straight waveguide structure with pulse emission with a value of Pa.

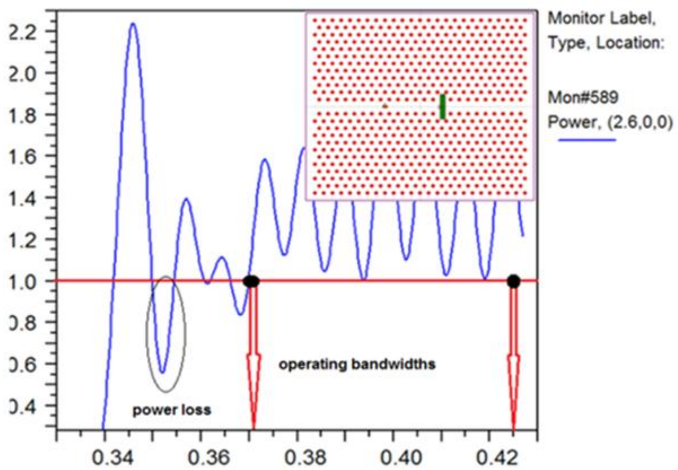

Fig4. *Straight waveguide structure and power transmission curve*

Now, a waveguide is created in the direction of KΓ (oblique waveguide) in the structure of crystal lattice the band diagram, Brillouin zone and waveguide area are illustrated in figure 5.

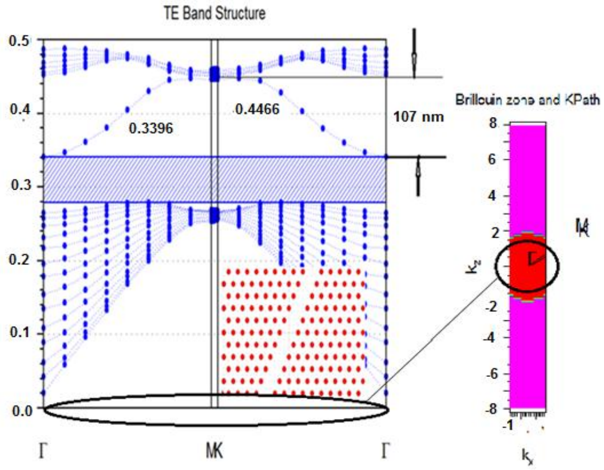

Fig5. *Oblique waveguide band diagram*

Simulated operating bandwidth of oblique waveguide structure is 107 nm which is increased compared to the structure of the straight waveguide. Operating frequency of the waveguide navigation rangeis 0.3396a/λ to 0.4460a/λ the intermediate frequency is 0.3931.

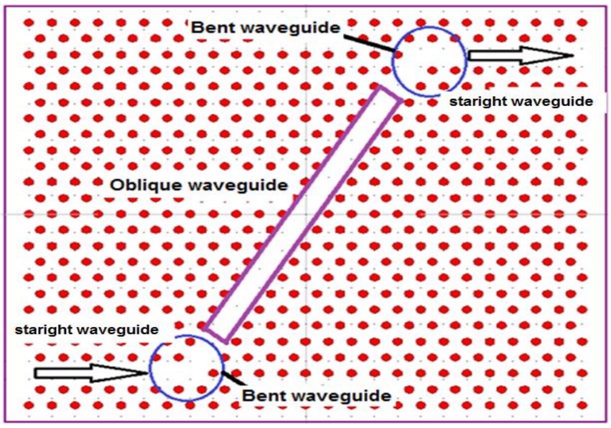

Fig6. *Shows structure of the oblique waveguide*

The structure of figure 6 is made up of one oblique waveguide connecting 2 straight waveguides. Two circles show bending waveguides which improve the intensity of the optical power transmission in the output.Figure.6 shows bandwidth of working area resembling the maximum power transmission in the output waveguide. According to figure 6, design of the optical logic gate in the period of bandwidth has a high flexibility in different frequencies.

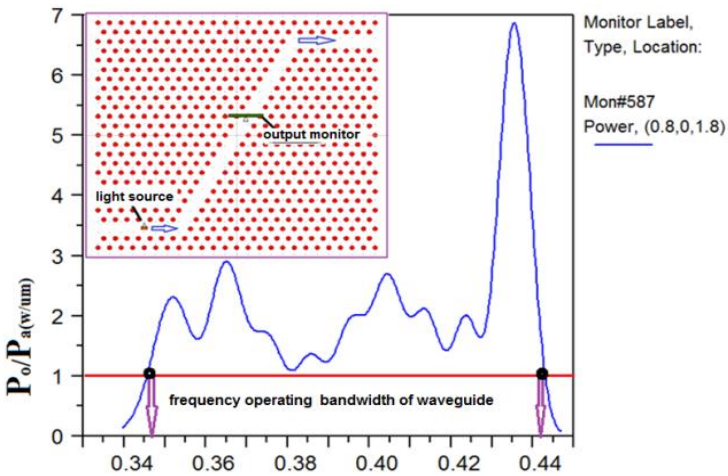

Fig7. *Oblique waveguide structure and power output curve*

To form logic gates, other basic waveguide connections such as cross-over waveguide and waveguide curve are used. For a better transmission in the output of the logic gate, the structure is formed like a bend. Waveguide bend is the coupling region between the input waveguide and the output waveguide. Length of the bend increases the coupling efficiency. The reason of increasing two mentioned parameters is the increase of coupling coefficient and length in the waveguide bend area. Increasing in the length of the bend leads to more coupling of the signal between input and output waveguide, the domain of passing power increases in the output bend (minimum losses). When we inject an optical power spectrum into the waveguide, constructive and destructive interference are created in some frequencies through the optical signal hitting the waveguide walls reflect of the light in the waveguide structure or waveguide bend. With a constructive bend, transmission of light in some frequencies is totally improved even the intermediate frequency in the output. According to figure 7, operating bandwidth and amplitude of optical power in the structure output with bend waveguide and oblique waveguide have been increased. In a comparison of oblique and straight waveguide, looking at the comparison made between 2 simulated figures of 7 and 4; it is obvious that the power transmission in a specific bandwidth is high for oblique waveguide structure. The reason is the presence of all directions of wave¬ vectors oblique waveguide direction. This waveguide design compared to reference designs and other resources has a great innovation due to a simple geometrical change in shape which has not been investigated in other articles. Applying such structure can be seen in the design of logic gates, filters, de¬ multiplexers and other optical devices.

4. Designing and Simulation of an All-Optical NOT Logic Gate

The final structure to design an optical NOT logic gate consists of an oblique waveguide, cross-over straight waveguide and a scatter rod in the crossover area. The oblique waveguide can be considered as a bend of large length. The large length of the bend (oblique waveguide structure) has increased amplitude of the coupling coefficient compared with straight waveguide and caused maximum passing optical power [14].

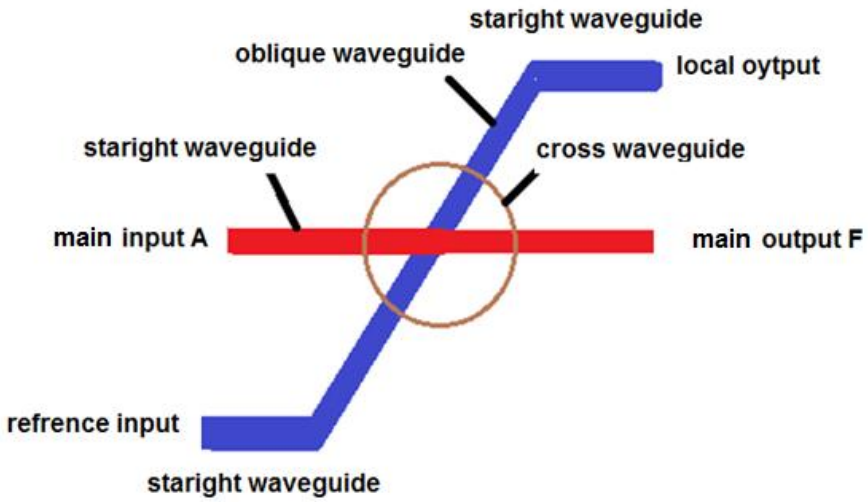

Fig8. *Schematic structure of NOT logic gate*

Structure of figure8 consists of a Ref input (reference input), input A (main input) and a F output (main output) as well as minor output. The input A is as the main input of the circuit. Input Ref works as an operator in such a way that fulfills NOT function. The F output is the main output of the circuit. The second output is used in the structure to fulfill NOT function using scatter rod. If the second output is not created in the structure amplitude of the main output, in both states of uni-input and dual-input will be increased and it will make the logic gate to be high in all cases. At first, we deal with structure of the logic gate without making any change in the center of the cross-over. The input signal for both inputs is assumed to be cw (continues wave). The output amplitude is simulated in two states of with and without main input. Figure 9 shows the structure of the NOT logic gate and power transmission versus time. When an input signal (A input) is in low mode, the reference signal moves toward A input and passes a few from the main output (0.04) and when the input signal A is in high mode, the total of two signals of A and Ref is scatterd inside the crystal lattice and the output signal is very naive.

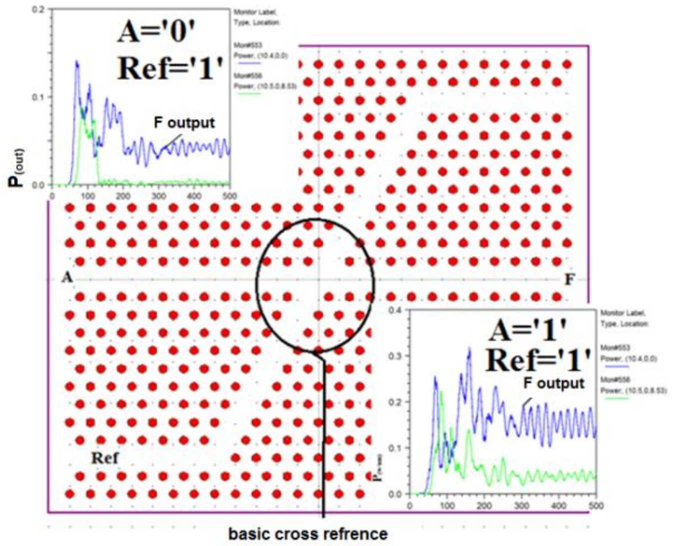

Fig9. *All optical NOT logic gate and power transmission curve for 2 ways in the input*

The reason for scattering is the destructive interference of two signals in the waveguide crosses over area. Therefore, the output amplitude of the logic gate will be in low mode in both input phases. We can make use of photonic limiter (waveguide or ring resonator) in the output of logic gate, but the consumption power increases with applying limiter [15]. Now we put a rod in center of the crossover of waveguide for scattering with input signal. Figure10 shows simulated amplitude of the output optical signal in the low mode of A input. The position of the rod is determined through trial and error and comparison of the results of the power pass in the output.

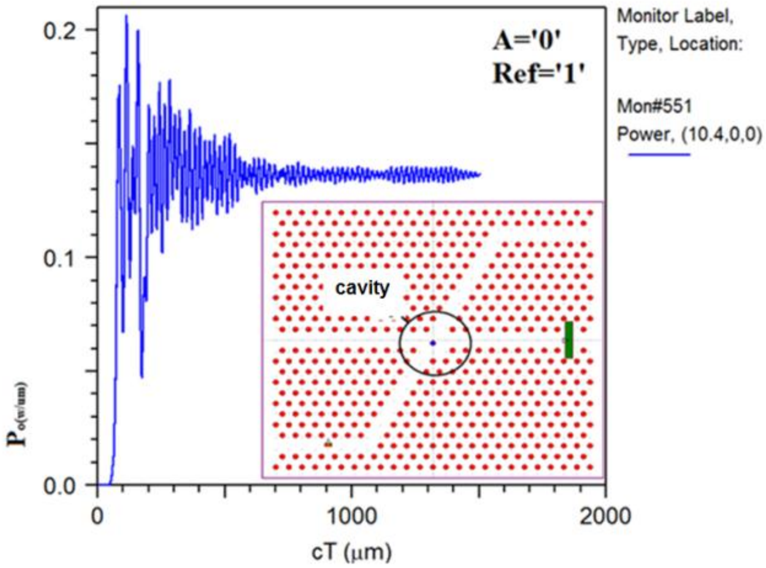

Fig10. *Waveguide cross-over structure together with cavities and optical power transmission curve.*

Position of the rod becomes (0.3 a and 0.5 a), (a is the lattice constant). One of the structure rods near the bent is omitted for a better passing of the optical power in the output waveguide. Picking this rod, the curve length is increased in the crossover area which results in more passing of power in the output waveguide. At first, we assume radius of the scatter rod to be equal too ther rods of the structure. When input optical signal is low, Refinput signal passes the oblique waveguide and after hitting the scatter rodem it's towards the F output waveguide. The logic gate output will become high. However, transmission power range in the output is above 1.1. The decrease in the radius of the scatter rod will lead to increase in the waveguide navigation area and output signal increases. The radius of scatter rod will be increased for the proper performance of the logic gate. The best result for the radius of the scatter rod becomes 0.225a. Now, we will deal with status of the output by applying high signal at an input. When two input signals reach the crossover area, a destructive interference occurs in the cross-over area. Figure 11 shows total structure of NOT logic gate an dits transmission curves for two modes in the input. Length of A input waveguide is not the same as that of Ref. Inequalities of the input waveguide length will lead to a time difference of two input signals in the crossover area. Therefore, a phase difference will be created among two input signals. Such difference in phases leads to destructive interference in the crossover area of the logic gate structure.

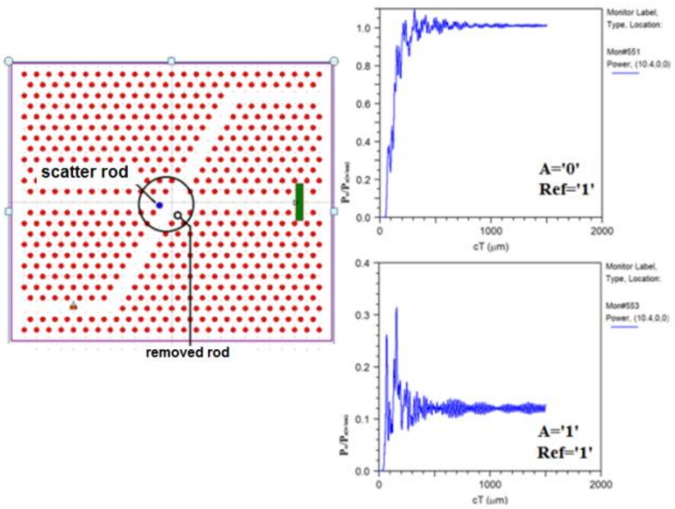

Fig11. *Structure of NOT logic gate together with power transmission curve*

Simulated value at output of the logic gate is 0.11for high an input signal. According to the simulated values in two modes; the performance of all-optical logic gate is NOT. The simulated power consumption is 200mw.

5. Conclusion

One of the features of the suggested plan is simple structure and absence of non-linear rods in the structure of the logic gate. The switching time for the proper performance of the suggested logic gate is simulated 0.51 ps. The Extinction ratio of the suggested logic gate is 9.6 dB. The suggested design in this article is for wavelength of 1.55μm and lattice constant of 0.609 μm. The simulated power consumption is 200mw. Since non-linear material was not used in the suggested design, the consumption power range for all optical logic gate switching has been reduced with a well-designed mechanism.

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