~~All~~Proof-of-concept for an all-optical AND gate ~~using~~with photonic-crystal quantum-dot semiconductor optical amplifiers

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An ~~All~~all-optical AND gate ~~using~~that uses photonic-crystal (PC) quantum-dot semiconductor optical amplifiers (QDSOA) is ~~presented~~designed and simulated herein ~~in this paper~~. ~~We numerically analyze the~~ The input–output characteristics of the gate are numerically analyzed ~~by~~ using rate equation ~~model~~modeling to prove ~~and show~~ that the gate can operate at 160Gb/s. ~~Moreover, in order to show the effectiveness of the proposed gate, we compare the~~ The proposed gate is compared with the ~~with conventional one~~design that uses an optical gate to evaluate its effectiveness ~~in terms of~~ with regard to ~~degree of integration, energy~~signal output, device size, and power consumption ~~and performance~~.

Introduction: Owing to progressing technology, ~~High~~high-speed and large-capacity data transmission is required to cope with ~~expanding~~increasing network traffic ~~data[1].~~ [1]. In current optical ~~network,~~networks, an optical signal ~~goes~~travels to its destination through optical ~~fiber with being~~fibers, and the signal is affected by noise~~.~~ along the way. Thus, re-amplification, re-timing, and reshaping ~~operations~~of the signal are essential for a reliable optical network~~. These days, electronic devices realize~~ operation. Currently, electronic components are used to implement these operations ~~and the problems are their~~; however, these components have low processing speed ~~limitation~~ and consume high energy during optical-to-electrical signal conversion and vice versa~~energy consumption required for optic-electric/electric-optic conversion[2]. In order to cope with these problems, all-optical signal~~ [2]. Signal processing ~~is required and many~~ equipment that uses all-optical components can avoid these limitations, and researchers ~~worked on and developed~~are actively pursuing all-optical signal processing components. Quantum-dot semiconductor optical amplifiers (QDSOA) are optical devices ~~which realize this technology. QDSOA is one of these devices which~~that can be useful in many applications owing to its relatively fast gain recovery time and nonlinear optics ~~because of it's fast gain recovery time and nonlinear optics effect~~[3]. ~~QD's~~The confinement of electrons and electron holes in QDs enables fast gain recovery, and ~~SOA's~~ gain saturation ~~enables~~ in the SOA leads to the nonlinear optics ~~effect, respectively.~~. ~~On the other hand~~In contrast, ~~the~~ photonic-crystal (PC) is a dielectric material ~~which consists~~with a periodic pattern of two different refractive indexes; therefore, ~~periodically. The lightwaves in specific~~ light waves of a single bandwidth cannot propagate through ~~the~~ PC. PC waveguides (PCWs) ~~use~~exploit this characteristic ~~which can be obtained~~ with a line-shaped recession in a PC slab ~~with creating a line-defect. They can confine the lightwaves~~. This linear recession confines the light waves in the directions perpendicular and parallel to the direction of ~~lightwaves~~ propagation. Moreover, ~~their~~the dispersion relation between the PC refractive indices can ~~slow down~~ decelerate ~~lightwaves~~the wave velocity, which can be useful ~~when~~ in cases wherein ~~they are~~a PCW is combined with an SOA or QDSOA.

Similar to electronic logic gates, all-optical logic gates (AOLGs ~~are the applications of all-optical devices which can operate~~) can manipulate binary inputs~~.~~. Although many AOLGs ~~using various all-optical devices~~ have been developed using a variety of optical materials, the length of these ~~gates is~~ AOLGs tends to be larger than ~~one~~ that of electrical logic gates ~~because~~since all-optical ~~devices require certain length~~components must be long enough to ~~operate as a component~~accommodate the reflections of ~~AOLGs~~the signal. For instance, a ~~length of~~typical QDSOA is ~~about~~ approximately ~~2mm~~2-mm long [4], whereas the ~~one of transistors,~~equivalent transistor used ~~for~~in commercially available electronic devices~~,~~ is ~~about~~ approximately ~~14nm~~14-nm long [5]. Few ~~researches discuss about~~studies have focused on the length of ~~device which~~the components in optical logic gates, although this is an important ~~factor for~~concerning the ~~developing~~ development of devices with high-density ~~integrated~~integration and ~~less~~minimal energy consumption ~~device. Thus,~~, ~~we~~ Therefore, ~~propose PC-QDSOA assisted~~ an all-optical AND gate~~.~~ that uses PC-QDSOA components is proposed herein. AND ~~gate plays~~gates play an important role for multiplexer and demultiplexer circuits ~~whose applications are~~ that are commonly used in communication ~~system~~systems, computer memory, and arithmetic logic ~~unit. In order to show~~units. To demonstrate the effectiveness of the proposed gate, we numerically ~~analyze the~~ analyzed its input–output characteristics ~~of the gate by~~ using rate ~~-~~ equation~~equation~~ ~~model~~models. To our knowledge, ~~there is~~ no research has been conducted ~~about~~ on the ~~numerically analyzing~~numerical analysis of a PC-QDSOA ~~assisted~~ all-optical AND gate yet. ~~The~~Our results ~~in this paper show~~ indicate that ~~the realization of the~~an all-optical AND gate ~~is feasible~~ with the proposed PC-QDSOA ~~assisted all-optical AND gate~~ waveguide could feasibly operate at ~~160Gb~~160 Gb/s and ~~the proposed gate~~ can achieve ~~9dB~~a maximum of 9-dB extinction ratio (ER~~) at most. Furthermore, we show the required~~). In addition, relatively low-current injection ~~for~~ is required when using the proposed all-optical AND gate ~~can be reduced with using the proposed gate~~design.

PC-QDSOA model: Fig. 1 schematizes ~~The schematic diagram of~~ a PC-QDSOA waveguide ~~is illustrated in Fig.1~~. The PC-QDSOAs used in this study ~~are composed of~~ comprise GaAs~~, Ino.15Gao.85As and~~ and Ino.15Gao.85As and include InAs ~~as an~~at the active region to enhance the optical power ~~around~~by approximately 1.3 /im [6]. ~~The population~~Population inversion in the active regions of the amplifiers is achieved by passing current through laterally doped p+–p–n+ structures. ~~Also, the waveguide of the PC-QDSOA is~~The W1 PCW waveguide ~~wherein~~of the PC-QDSOA allows slow light ~~can~~to be achieved

Comment [Editor1]: Remark: Please verify if the edit retains your intended meaning.

Comment [Editor2]: Remark: Please verify if the edit retains your intended meaning.

Comment [Editor3]: Remark: Please verify if the edit retains your intended meaning.

Comment [Editor4]: Remark: Note that this sentence has been edited to explain why all-optical components should be long enough. Please verify if the edit retains your intended meaning and clarify further if required.

Comment [Editor5]:
Tip: Serial comma
In American English, a comma (called serial or oxford comma) is inserted before "and" in a series.

with ~~either~~ zero group~~-~~velocity ~~dispersion~~ and zero third~~-~~order dispersions ~~in~~at a specific bandwidth. The waveguide ~~can be achieved~~is fabricated by creating a ~~line defect~~ line-shaped recession in a PC slab ~~PC, which can be obtained~~, and the slab is fabricated by creating periodic round ~~vacancy periodically~~vacancies on n-~~cladding~~ and p-~~cladding~~clad regions [7].

The operation of the PC-QDSOAs can be studied theoretically ~~studied by means of a~~ using the rate- equation~~equation~~ model [8]. InAs QDs ~~consists of~~comprise a ground state (GS), an excited state (ES), and an upper state (US). ~~A quantum well~~Quantum wells

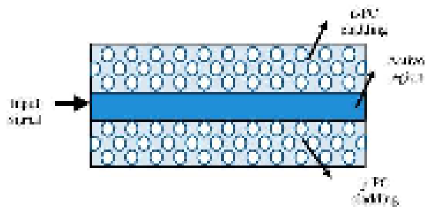


Fig. 1. Schematic ~~diagram~~ of the PC-QDSOA waveguide

(~~QW) is~~QWs) are the common carrier reservoirs ~~for~~in QDs. ~~Due to variability in the size and shape of QDs~~ QDs exhibit different sizes and shapes ~~with use of~~ when using the Stranski~~-~~–Krastanov mode~~, the~~; therefore, carrier dynamics in the QDs can be described ~~by~~ using 1088 variables. Thus, ~~a~~the rate equation ~~of~~for the PC-QDSOA is as follows:

Comment [Editor6]: Remark: Please clarify if you mean W1 PCW herein and consider revising.

Comment [Editor7]: Remark: Please clarify why this mode is used herein.

Comment [Editor8]: Remark: Please clarify your intended meaning herein.

$$[illegible] \quad (1)$$

$$[illegible] \quad (2)$$

$$[illegible] \quad (3)$$

$$[illegible] \quad (4)$$

The term $f_{Wj}^{(v)}$ represents the carrier occupancy of the QW. Likewise, $f_{c(v)u;j}$, $f_{c(v)e;j}$, and $f_{c(v)g;j}$ ~~fu'jj^' fe^,~~ represent~~s~~ the carrier occupancy of the jth group of US, ES, and GS, respectively. The term r_k is the optical confinement factor at wavelength X_k. The ~~term~~terms $P_{k,in}$ and P_p ~~represents~~represent the power

Comment [Editor9]: Remark: Please insert a comma after Equations (1), (2), and (3) and a period after Equation (4).

of the ~~feth~~kth photon mode and probe signal, respectively. The term $a(\lambda)$ represents the loss coefficient at ~~a~~the wavelength λ, which ~~can be~~is the sum of the scattering and absorption losses. The term $g_{mod}(t, \lambda_k)$ is the effect on linear modal gain ~~affected~~caused by slow light, and it can be expressed as the product of the slowdown factor, optical- confinement~~confinement~~ factor, and linear material gain of the active region. The term g^g ^ is the linear optical gain that the GS (ES) of the j-th QD group ~~gives~~ provides to the ~~fe~~k-th ES photon mode ~~is given~~. More details about the PC-QDSOA structure ~~can be found~~ are provided in reference [8].

Comment [Editor10]: Remark: Please clarify your intended meaning herein.

AND gate model: ~~The~~ Fig. 2 schematizes ~~ic diagram of~~ the PC-QDSOA ~~assisted~~ all-optical AND gate ~~is shown in Fig.2~~. ~~The AND operation principle is as follows~~Following the labels in Fig. 2, the operation of AND gate is described as follows: a modulated-data signal A (at wavelength λ_A) and a clock signal (at wavelength λ_C) are ~~injected into the~~ input to PC-QDSOA1. ~~Then the signal~~Signal A will induce ~~less~~low gain amplification on ~~a~~the clock signal via cross-gain modulation (XGM) in ~~the~~ PC-QDSOA1 ~~and~~; therefore, the logic ~~outcome~~output is always NOT A. ~~In the same way as~~Repeating this operation, ~~a~~the modulated-data signal NOT A (at wavelength λ_C) and a modulated-data signal B (at wavelength λ_B, which can be ~~the same as~~equal to the wavelength of ~~data~~signal A) are ~~injected into the~~

input to PC-QDSOA2, and the logic ~~outcome~~output is then A AND B.

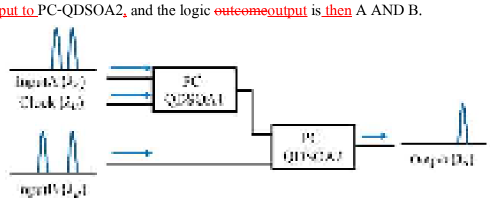


Fig. 2. Schematic ~~diagram~~ of the PC-QDSOA ~~assisted~~ all-optical AND gate

Results: ~~We numerically analyze the~~ The operation of the proposed gate ~~with~~design is numerically analyzed using MATLAB 2016b and Optisystem 14.0.0. The physical parameters used for solving the rate equation ~~can be found~~are provided in reference [8]. Table 1 ~~shows~~lists the fixed parameters used for ~~following~~the numerical analysis ~~in this paper~~. The pulses ~~are~~were Gaussian-shaped ~~pulses~~.

Table 1: ~~The fixed~~Fixed parameters used ~~for following~~in numerical analysis

Parameter	Value	Unit
Maximum power of Input A	10	mW
Maximum power of Input B	1	/W
Maximum power of Clock	100	/W
Wavelength of Input A	1307	nm
Wavelength of Input B	1307	nm
Wavelength of Clock	1310	nm
Full width at half maximum of pulse	1.2	
Transmission speed	160	Gb/s

To evaluate the proposed gate, ~~we use~~ the eye diagram, ER, and Q-factor are used as ~~appropriate~~ metrics. The ER~~extinction ratio~~ can be represented as $ER[dB] = 10\log_{10}(P_{min}/P_{max})$. P_{min} represents minimum ~~p°wer~~power of the binary signal "1", and P_{max} represents the maximum power of the "0" signal ~~"0"~~. The Q-factor can be represented as $Q = (S_1 - S_0)/(\sigma_1 + \sigma_0)$ [9] where S_1 and S_0 are the average ~~power~~powers of signals "1" and "0" and σ_1 and σ_0 are the standard deviations of those signals.

Fig. 3 shows the ~~analysis~~simulation results ~~of~~for the input-output characteristics ~~when~~with 6-mA current injection ~~is 6mA~~. Fig. 4 shows an eye diagram of the output signal. The ER and Q-factor ~~of~~for the output signal are 8.58 dB and 7.41, respectively. ~~From these~~These results~~, it is said~~ show that the proposed gate design can operate as an AND gate at 160 Gb/s [10]. ~~On the other hand, because~~Since the gain recovery time varies ~~due to~~with the level of current injection, we ~~have~~also investigated the effect ~~on power~~ of varying current injection ~~to~~ on the power output from the proposed AND gate. ~~Fig.~~Figs. 5 and ~~Fig.~~6, respectively, show the ERs and Q-factors of the output signals ~~under~~with different ~~current injection, respectively.~~injected currents. The ERs and Q-factors ~~are improving~~improve with increasing current injection because pattern ~~effect is decreasing.~~ effects decrease. When current injection ~~is over 9mA, there is few~~ exceeds 9 mA, the ERs change slightly ~~in ERs~~ because the maximum gain- recovery~~recovery~~ time is limited by carrier-relaxation ~~time~~ and capture times.

Comment [Editor11]: Remark: Please explain more in this sentence about how these ER and Q-factor results are related to the device functioning as an AND gate.

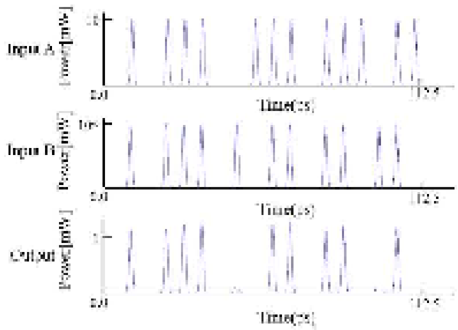


Fig. 3 *Input~~-~~-output characteristics ~~of~~for PC-QDSOA all-optical ~~assisted~~ AND gate ~~operation~~ when current injection is ~~6mA~~6 mA*

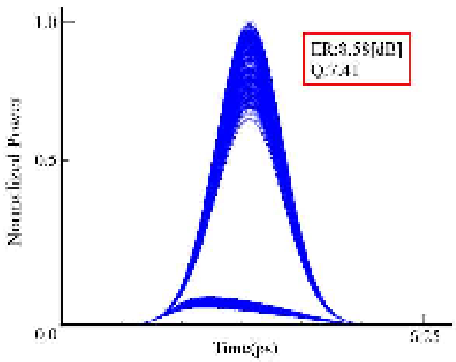


Fig. 4. Eye diagram of the output signal ~~when~~with 6-mA current injection

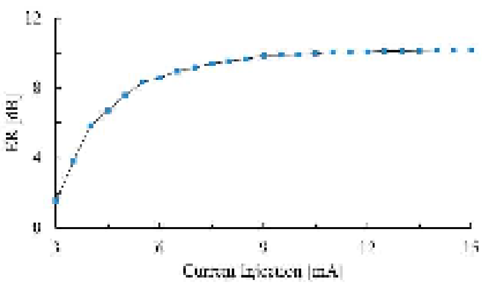
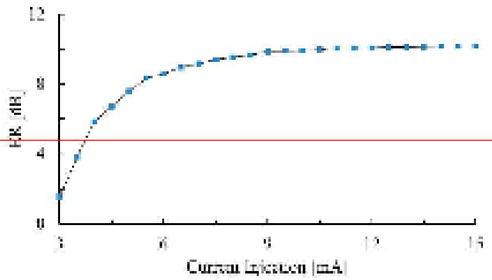


Fig. 5. ERs with varying current injection ~~is 6mA~~



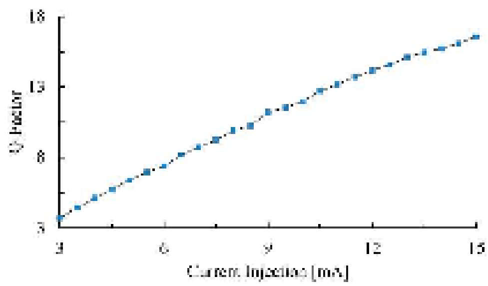
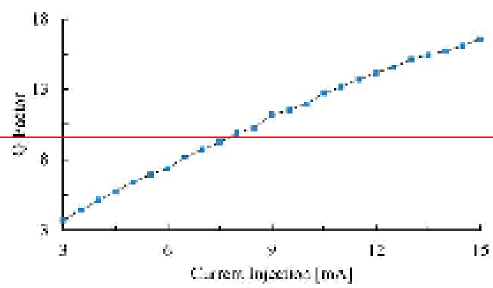


Fig. ~~5. ERs under different~~6. Q-factor with varying current injection



~~Fig. 6. Q-factor under different current injection~~

~~In order to show~~

~~To quantify~~ To quantify the effectiveness of the proposed gate, ~~we compare~~ the proposed AND gate is compared with ~~the one~~a QDSOA~~-~~assisted~~, whose~~ gate without PC components. This design follows the same schematic ~~diagram is same~~ as the proposed ~~one. The physical~~design. Physical parameters and ~~numerical analysis method of~~the methods used to analyze this QDSOA ~~can be found~~design are provided ~~-~~in reference [4]. ~~Fig.~~Figs. 7 and ~~fig.~~8 ~~show the comparison of current injection required to obtain each~~, respectively, plot ERs and Q-factors vs. current injection for QDSOA~~-~~assisted AND gate and the proposed ~~one, respectively. From fig.7, it is said that to~~design. To obtain ER ~~of about~~ approximately ~~7.5dB,~~7.5 dB, the QDSOA~~-~~assisted AND gate requires ~~3000mA~~3000 mA, whereas the proposed ~~AND gate~~design requires only ~~5mA.~~5-mA injected current. Likewise, ~~from fig.~~Fig. 8~~,~~ shows that to obtain a Q-factor ~~of about~~ approximately 5, the QDSOA~~-~~assisted AND gate requires ~~2800mA~~2800-mA injected current, whereas the proposed ~~AND gate~~design requires only ~~4mA~~4 mA. Moreover, the ~~device length of the~~ QDSOA is ~~2mm~~2-mm long, whereas the ~~one of the~~proposed PC-QDSOA is 125~~/m. From these results, less~~ μm. This comparison demonstrates that the AND gate reduces energy consumption and ~~less~~device volume ~~AND gate can be obtained with use of the proposed gate~~compared with all-optical AND gates reported in the literature.

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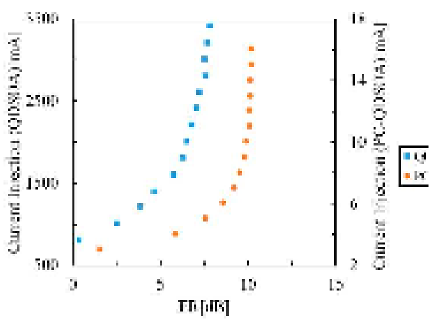

Fig. 7. ERs under different current injection

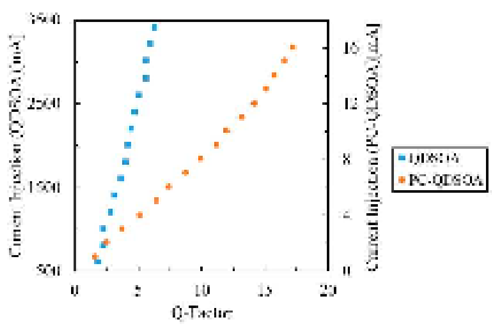

Fig. 8. Q-factor under different current injection

Conclusion: We ~~have proposed~~designed a PC-QDSOA ~~assisted~~ all-optical AND gate ~~operating~~ that can operate at ~~160Gb~~160 Gb/s ~~and evaluated the performance~~. The measures of ~~the proposed gate by using~~ eye diagram, ER, and Q-factor~~. The results~~ quantify the design's performance. Numerical analyses show that the proposed gate can operate as an AND gate at ~~160Gb~~160 Gb/s when current injection is over ~~6mA and better~~6 mA. This performance can be ~~achieved with~~ improved by increasing current injection ~~because~~, as this would decrease pattern ~~effect decreases~~ effects.

Comment [Editor13]: Remark: Note that the terms "PC-QDSOA-assisted AND gate" and "PC-QDSOA all-optical AND gate" were interchangeably used. We have therefore used "PC-QDSOA all-optical AND gate" throughout the document for consistency.

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Comment [Editor14]: Remark: Please provide page numbers for the reference wherever applicable.

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