All Optical Logic Processing Using a Transistor Laser Photonic Integrated Circuit

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***Abstract*—The transistor laser is the ideal platform for integrated photonics due to its multiple functionality as a bipolar junction transistor as well as a three-terminal laser with internal collector junction photon-electron conversion feedback. In this work integrated all-optical logic NOR gates are constructed and realized with the transistor lasers as the circuit components.**

Keywords—Transistor laser; optical logic; photonic integrated circuit

I. Introduction

With the increasing data rate, conventional integrated circuit (IC) technologies based on transistors such as CMOS and BiCMOS face scaling challenges from both intrinsic device scaling [1] as well as the scalability of metal interconnects [2]. For applications that require high data rates such as high-performance computers and data centers, optical interconnects have been acknowledged as the superior solution and have been widely deployed on the board-to-board or rack-to-rack levels. As the data rate bottleneck ultimately reaches the chip level, a solution is required to enable on-chip processing and transmission of optical signals. This has been done commercially in long-haul applications in large-scale photonic integrated circuits (PICs) [3], but an efficient fundamental building block in the form of an all-optical logic gate is still required for complex monolithic logic processing applications. Previous demonstrations using optical interference phenomena [4] or epitaxial combination of discrete semiconductor structures [5] are constrained by bandwidth, size, and processing complexity.

The transistor laser [6] is the ideal platform for integrated photonics due to its dual functionality as a bipolar junction transistor and a laser transmitter. The light output can be modulated directly using the base current (quantum-well carrier recombination) or the collector voltage (photon-assisted tunneling) [7], greatly reducing the complexity of the transmitter circuitry. In this work, we demonstrate a novel PIC in the form of an all-optical NOR gate using the transistor laser.

II. All-Optical NOR Gate Design and Fabrication

As a proof-of-concept design for transistor laser-based photonic integrated circuit, a NOR gate has been selected. A NOR gate is a universal logic gate that can act as the fundamental building block for all other logic functions.

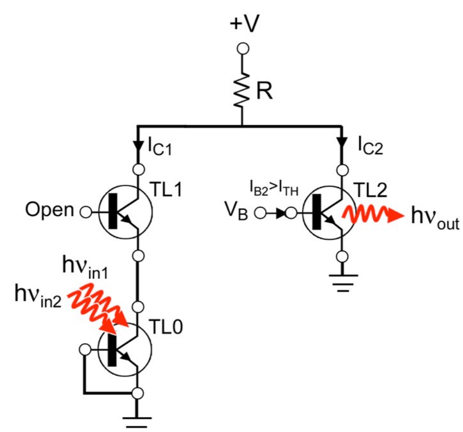

Fig. 1. Circuit diagram for the transistor laser all optical NOR gate. TL2 acts as a regular transistor laser, TL1 acts as an active load, and TL0 acts as a photodiode

The circuit implementation of the transistor laser all-optical NOR gate is shown in Fig. 1. The entire gate consists of three transistor lasers divided into two branches, sharing a constant voltage source V and load resistor R. The right branch is TL2 which acts as a normal transistor laser biased at a fixed base current I_{B2} and a collector current I_{C2}. When I_{B2} exceeds the lasing threshold of TL2, TL2 will generate a constant optical output $h\nu_{out}$. The left branch provides the control signal to regulate the right branch collector current I_{C2}. TL0 acts as a photodiode with its collector tied to the emitter of TL1, which acts as an active load.

The functionality of the all-optical NOR gate is explained as follows: in a logic "1" case, no optical signal input is applied to TL0. This causes no current to conduct on the left branch (I_{C1} = 0), and the right branch operates as a conventionally biased transistor laser in the active mode with I_{B2} greater than the lasing threshold, and the output of the NOR gate is "high"; in a logic "0" case, a nominal optical input is incident on TL0, and the resulting photocurrent sets the collector current I_{C1} of the left branch, inducing a non-zero collector-emitter voltage on TL1; the induced voltage causes the total voltage on the combined node to rise, increasing the collector-emitter bias of TL2, allowing more electrons to tunnel towards the collector through photon-assisted tunneling process [7], increasing the collector current, decreasing the light output, and switching the NOR gate output to "low" state. By using multiple input signals and careful circuit design, NOR function can be realized because any optical signal input incident upon TL0 would result in the optical signal output at TL2 to switch from high to low.

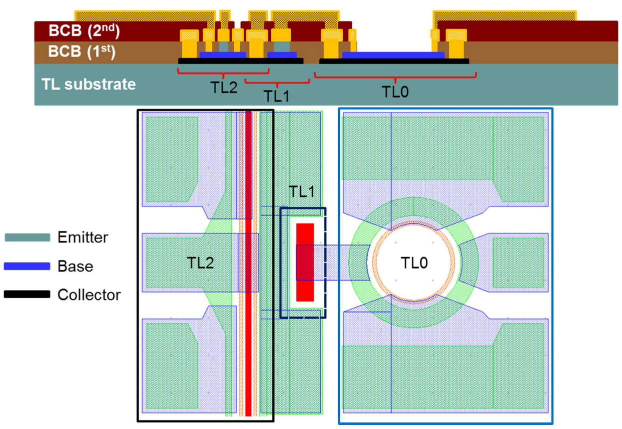

Fig. 2. Lateral cross-section and top view design diagrams of the transistor laser-based all-optical NOR gate showing the interconnections between components.

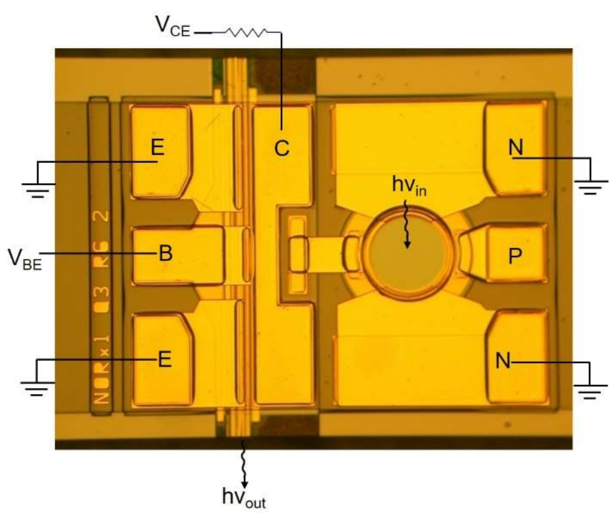

Fig. 3. Fabricated transistor laser-based all-optical NOR gate; the biasing scheme as well as input/output signal paths are also drawn on top.

Figure 2 shows the circuit design of the NOR gate that integrates TL0, TL1, and TL2 in a highly compact form. The interconnections between components are visualize in the lateral cross-section view. TL2 is implemented as a regular transistor laser with its collector pad shared with TL1. TL1 acts as an active load and is implemented as a normal transistor in a floating base configuration. TL0 is implemented as a p-i-n photodiode by utilizing the base-collector p-n junction of the transistor laser. The n-contact of the TL0 photodiode is connected to the emitter of TL1.

Figure 3 shows the fabricated integrated circuit using a similar process to [8] with the addition of an integrated photodiode. In order to establish the metal interconnects, the device is fabricated using a two-step planarization and via process. After front-end process, the wafer is thinned down to 150 µm thickness and cleaved to form edge-emitting facets. Each individual die is then indium-bonded to a copper substrate for handling during testing.

III. Characterization and Logic Testing

The finished devices are measured on a probe station equipped with a modular laser source and a photodetector. The testing configuration has been indicated in Fig. 3. The base current bias (V_{BE}) is provided using a coplanar GSG probe. The collector voltage bias (V_{CE}) is provided by a DC probe in series with a variable load resistor to define the load line of TL2. A second DC probe grounds the n-contacts of the TL0 photodiode. An external laser source provides the input optical signal to TL0 via a fiber probe. Finally, the light output from the facet is collected with a focusing lens and free-space coupled into a large-area power meter.

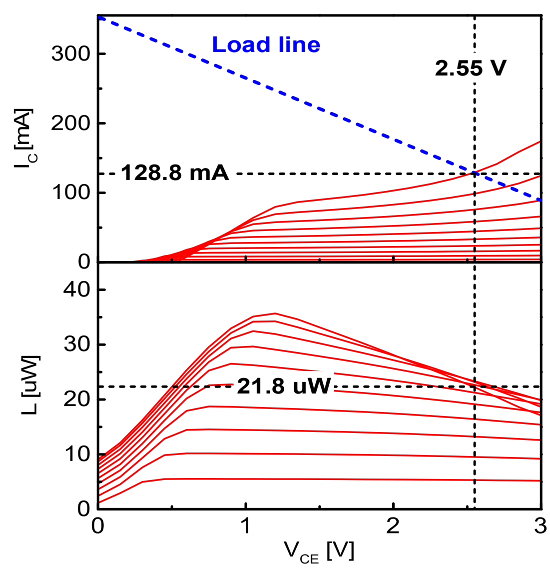

Fig. 4. L-I-V curves of the transistor laser (TL2) in the all-optical NOR gate showing spontaneous light emission. The blue line indicates the load line set by the voltage supply and load resistor of arbitrary values as an example.

Before testing the logic function of the entire circuit, the individual components of the NOR gate are characterized. The family L-I-V curve of the output transistor laser TL2 is shown in Fig. 4, with a base current bias of 0-50 mA

($\Delta I_B = 5\,mA$). The collector current exhibits larger electrical gain compared to a typical transistor laser, without showing gain compression which signals the transition from spontaneous to stimulated light emission [6]. The measured light output of the transistor laser is very weak due to the spontaneous nature of the light emission, and the non-directionality of light emission makes the coupling efficiency of the focusing lens very low. It is suspected that the transistor laser suffers from a prohibitively high lasing threshold caused by poor heat conduction or added resistance from the double via process.

Next, the responsivity of the TL0 photodiode is measured using an 850 nm oxide-confined VCSEL previously reported in [9]. The average responsivity of the photodiode is measured to be 0.0346 A/W, shown in Fig. 5. The low responsivity is within expectation and can be attributed to the epitaxial structure of the transistor laser, which only contains 60 nm of depleted GaAs in the base-collector junction as the light absorption region.

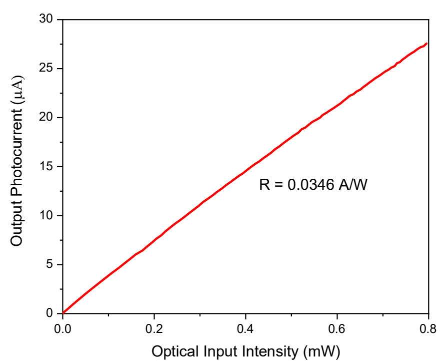

Fig. 5. Responsivity of the TL0 photodiode measured using an 850 nm external VCSEL.

Finally, the logic function of the optical NOR gate is characterized. First, TL2 is biased at a base current of 50 mA to maximize the optical output of the NOR gate; the voltage supply is set to 4 V with a load resistor R of 11.3 Ω, yielding a TL2 collector-emitter voltage of 2.3 V, which correctly places TL2 in the collector tunneling modulation region. The light from the modular laser source is coupled to the TL0 aperture and is switched on and off manually to provide a square wave input optical signal. Note that in this case the optical NOR gate acts much like an inverter because there is only one input signal; potentially testing for the NOR functionality can be done by coupling two different light sources into the fiber or by using a multi-level input signal, but the experiment setup was limited at the time of the measurement.

Referring to Fig. 4, as the collector voltage is increased due to the presence of an optical signal, the operating point of TL2 shifts along the load line set by the supply voltage and the load resistor, and the optical output will be reduced. Fig. 6 shows the logic timing diagram with an input signal provided by a single modular laser source to demonstrate single-input NOR (or inverter) functionality. The logic ‘1’ threshold is 21.85 μW and the logic ‘0’ threshold is 21.75 μW, respectively. The fluctuations in the “0” and “1” levels are primarily due to the sensitivity of the large-area power meter.

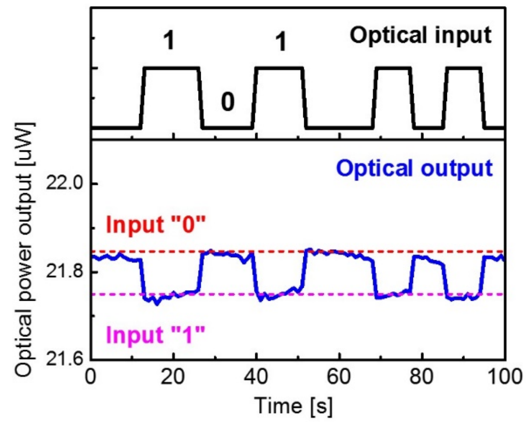

Fig. 6. Logic timing diagram for the transistor laser-based all-optical NOR gate. The logic ‘1’ threshold is 21.85 μW and the logic ‘0’ threshold is 21.75 μW.

IV. Conclusion and Future Work

In conclusion, an all-optical NOR gate based on transistor laser integrated circuit is designed and fabricated in a highly compact form. The logic NOR gate consists of transistor laser devices functioning differently as photodetector, as active load, or as laser emitter. The logic functionality of the NOR gate is tested in the case of single input. While the transistor laser only emits spontaneously and thus the signal level is severely limited, the NOR gate logic functions correctly nevertheless. This work is the first demonstration of using transistor laser as the building block of photonic integrated circuit for logic computation.

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References

[1] M. T. Bohr and I. A. Young, "CMOS Scaling Trends and Beyond," in *IEEE Micro*, vol. 37, no. 6, pp. 20-29, Nov./Dec. 2017.

[2] M. A. Taubenblatt, "Optical Interconnects for High-Performance Computing," in *Journal of Lightwave Technology*, vol. 30, no. 4, pp. 448-457, Feb. 2012.

[3] F. Kish *et al*., "From Visible Light-Emitting Diodes to Large-Scale III–V Photonic Integrated Circuits," in *Proceedings of the IEEE*, vol. 101, no. 10, pp. 2255-2270, Oct. 2013.

[4] T. A. Ibrahim, R. Grover, L. C. Kuo, S. Kanakaraju, L. C. Calhoun and P. T. Ho, "All-optical AND/NAND logic gates using semiconductor microresonators," in *IEEE Photonics Technology Letters*, vol. 15, no. 10, pp. 1422-1424, Oct. 2003.

[5] P. Zhou *et al*., "Cascadable, latching photonic switch with high optical gain by the monolithic integration of a vertical-cavity surface-emitting laser and a pn-pn photothyristor," in *IEEE Photonics Technology Letters*, vol. 3, no. 11, pp. 1009-1012, Nov. 1991.

[6] H. W. Then, M. Feng and N. Holonyak, Jr., “The Transistor Laser: Theory and Experiment,” in *Proceedings of the IEEE*, Special Issues on 50^{th} Anniversary of the LED vol. 101, no. 10, pp. 2271-2298, Oct. 2013 (Invited Paper).

[7] M. Feng, J. Qiu, and N. Holonyak, “Tunneling Modulation of Transistor Lasers: Theory and Experiment,” *IEEE J. Quantum Electron.*, vol. 54, no. 2, pp. 1–14, Apr. 2018.

[8] F. Tan, R. Bambery, M. Feng, and N. Holonyak, Jr," Transistor laser with simultaneous electrical and optical output at 20 and 40 Gb/s data rate modulation," in *Applied Physics Letters*, vol. 99, no. 6, p. 061105, 2011.

[9] H.-L. Wang, J. Qiu, X. Yu, M. Feng, and N. Holonyak Jr., “85°C Operation of 850 nm VCSELs Deliver a 42 Gb / s Error- Free Data Transmission for 100 meter MMF Link,” in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, 2018, p. W1I.6.