All Optical NOR Gate via Tunnel-Junction Transistor Lasers for High Speed Optical Logic Processors

Milton Feng, Ardy Winoto, Junyi Qiu, Yu-Ting Peng and Nick Holonyak, Jr.

Micro and Nanotechnology Laboratory, Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A., 61801 (mfeng@illinois.edu)

Abstract: *Tunnel-junction transistor lasers (TJ-TLs) is a critical element to form a universal electro-optical NOR gate and an optical bistable latch which can be developed into a compact chip-level solution for optical logic processors operating at GHz speed.*

Keywords: Optical Logic; Semiconductor Laser; Tunnel Junction Transistor Laser (TJ-TL); Optical NOR Gate.

Introduction

To fulfill the ever-expanding networked world, a revolutionary new computer technology is needed. The ultimate performance of today's digital electronic computer is limited by the RC time constant and carrier delay times of electronic logic. To circumvent these problems, an optical digital computer mimicking the electronic digital computer has been considered. However, the full application of optics has yet to be applied to digital computers because of the lack of suitable optical logic processors with adequate size and speed. Through intensive research efforts, the future high-performance digital computers should encompass advantage from photonics and electronics for flexible electronic functionality with highly parallel optical processing, optical interconnections, and optical I/O capabilities.

Transistor Laser Integrates Quantum-Wells and Tunneling into Heterojunction Bipolar Transistor

In 2005, a 3-port transistor laser (TL) was invented by Milton Feng and Nick Holonyak, Jr., fundamentally enables us to develop high-speed digital computation in the optical domain [1]. Different than the transistor invented by Bardeen and Brattain (1947) operated as a 2-port device with a base input (I_B-V_{BE}) and a collector output (I_C-V_{CE}), the transistor laser (TL) is a 3-port device (an integration of quantum-well into the base and intracavity photon-assisted tunneling in the collector junction of heterojunction bipolar transistor) with a base input (I_B-V_{BE}), a collector output (I_C-V_{CE}), and an optical output (L-V_{CE}).In contrast to the 2-port double heterojunction *diode* laser with a "slow" spontaneous carrier lifetime (~1ns), a "fast" recombination lifetime (< 23ps) can be realized in a *transistor* laser by tilting the injected carrier population and diffusing carriers across a thin, oppositely doped, QW base active region to remove slow recombining carriers, thus favoring only "fast" recombining carriers. Due to the thin-base of the TL, the emitter-to-collector (diffusion) transit time (τ_t) is on the order of ~ a few ps. Hence, the intrinsic spontaneous recombination speed in the base of TL can be "clamped" at the same magnitude as the base transit time. This has been confirmed experimentally. Recently, we demonstrated a light emitting transistor with base and emitter short as a tilted charge diode can have direct modulation bandwidth f_{-3dB} = 7 GHz (τ_B < 23 ps). Furthermore, a single QW-transistor laser was reported for a nearly resonance-free 20 GHz bandwidth and 22 Gb/s error-free data transmission. [2,3].

Tunnel Junction Transistor Lasers for Electro-Optical NOR Gate and Bistable Latch

Recently, we have shown a TL incorporating a tunnel junction in the collector (Fig. 1) [3] is more effectively controlled by changes in collector bias voltage, which makes possible direct voltage modulation in addition to the usual one of current modulation (at another terminal). The collector tunnel junction works as an additional source of hole re-supply to the base, and to recombination and competing with the usual base current. It can be used to enhance TL operation, and it can be quenched by Feng-Holonyak intra-cavity photon-assisted tunneling (FH-ICPAT) [4], thus adding significantly to TL flexibility and usage in logic circuits. Thus, the tunnel junction TL is an integrated optoelectronic device by itself combining laser, photodetector, transistor, and modulator within one device. The invention of tunneling-modulation transistor laser fundamentally enables us to develop high-speed voltage switching for digital computation in the optical domain.

The switching of TL2 for lasing state "Logic 1" and non-lasing state "Logic 0" is determined by the voltage-drop, which is unique to a TJ-TL. We are able to build an all optical NOR gate with three tunnel junction transistor lasers as shown in Fig. 2. TL0 functions as photodetector with base-emitter short; TL1 functions as a large resistor with base open; TL2 functions as transistor laser. TL2 will lase (ON) for V_{CE2} = 0.8 V when there is no optical input to the photodetector TL0. Here TL0 is biased at V_{CE0} = 0.8 V and no current flow in TL1, thus V_{CE1}= 0 V. This set TL2 V_{CE2} = 0.8V for the lasing state of "Logic 1" for a fixed base current I_B = 80 mA with coherent light output of ~ 95 μW collected by lens fiber as shown in the TJTL optical L-V_{CE2} characteristics in Fig. 2. In addition, the corresponding TJTL collector I_C-V_{CE2} characteristics

978-1-5386-4825-4/18/$31.00 ©2018 IEEE

are also illustrated in Fig. 2 with two operational regions, namely, spontaneous e-h recombination in the base QW (Black) for incoherent light output (LEDs) and stimulated e-h recombination (Red) for coherent light output (Laser).

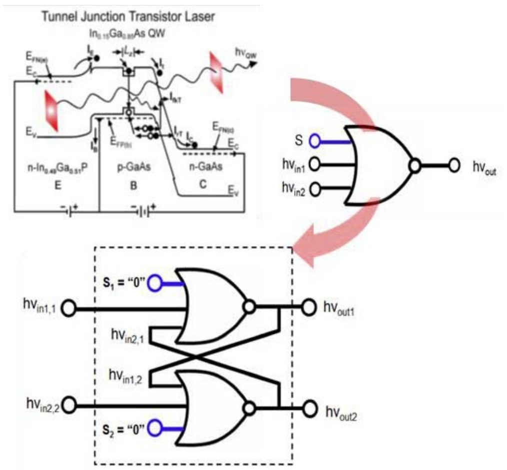

Fig. 1. (a) TL incorporating a tunnel junction in the collector (top) An optical bistable latch (bottom panel) build with two universal photonic NOR gate circuits, which are implemented by three-port TJ-TLs (top panel).

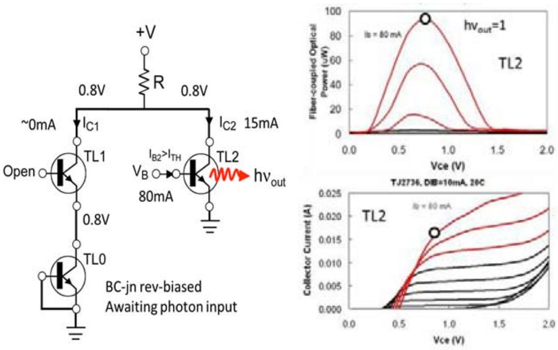

Fig. 2. All optical NOR gate with "Logic 1" implemented by inverted topology of three transistor lasers. TL2 will lase (ON) for V_{CE2} = 0.8 V when there is no optical input to TL0 (V_{CE0} = 0.8 V) and no current flow in TL1 (V_{CE1}= 0 V).

For an all optical NOR gate with "Logic 0" implemented by inverted topology of three transistor lasers as shown in Fig. 3. TL0 functions as photodetector with input $h\nu_{in1}$ or/and $h\nu_{in2}$. TL2 will not lase (Off) for V_{CE0} = 1.6 V when there are one or two optical inputs to TL0. In this case, the photodetector TL0 sets collector voltage V_{CE0}= 0.8 V with photo current flow through TL1 resulted in V_{CE1}= 0.8 V. Hence, TL2 operates as incoherent light output at V_{CE2}= 1.6 V for a load resistor R = 130 ohm as shown in Fig. 3 with the coherent photon density in the optical cavity is reduced below laser threshold via Feng-Holonyak Intra-cavity photon assisted tunneling (FH-ICPAT) as collector voltage V_{CE2} increases from 0.8 to 1.6 V. The TL2 switching operations from "Logic 1" to "Logic 0" are illustrated in collector I_C-V_{CE2} (R= 130 ohm) and optical L-V_{CE2} characteristics.

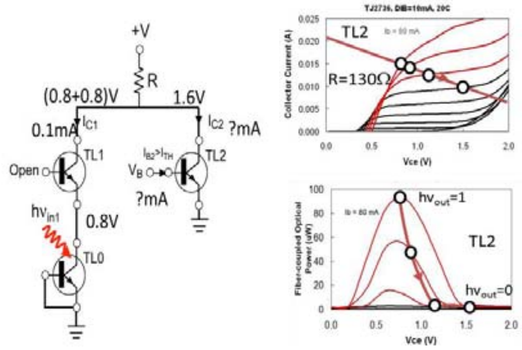

Fig. 3. All optical NOR gate with "Logic 0" implemented by inverted topology of three transistor lasers: TL0 functions as photodetector with input $h\nu_{in1}$ or/and $h\nu_{in2}$. TL2 will not lase (Off) for V_{CE0} = 1.6 V when there are one or two optical inputs to TL0.

Using the proposed TJ-TL-based electro-optical NOR gate, we have designed four different forms of bistable latch: (a) all-optical bistable latch, (b) electrical-in, optical-out bistable latch, and (c) optical-in, electrical-out bistable latch. Of course, (d) a simple all-electrical latch is possible and doesn't need to be described here.

Proposed Logic Table for (a) All-Optical Bistable Latch

$h\nu_{in1,1}$	$h\nu_{in1,2}$	$h\nu_{out1}$	$h\nu_{out2}$
0	0	No change	No change
0	1	0	1
1	0	1	0
1	1	Forbidden	Forbidden

Acknowledgements

This project is also supported by the National Science Foundation under grant 1640196, and the Nanoelectronics Research Corporation (NERC), a wholly-owned subsidiary of the Semiconductor Research Corporation (SRC), through Electronic-Photonic Integration Using the Transistor Laser for Energy-Efficient Computing, a Nanoelectronics Research Initiative (SRC-NRI) under Research Task ID 2697.001-Transistor Laser Based Circuits and Devices.

References

[1] M. Feng and N. Holonyak, Jr. "The Metamorphosis of the transistor into a laser", Optics & Photonics News (OPN), *Optical Society of America* page 44-49 (OSA), (2011)

[2] M. Feng, N. Holonyak, Jr., H.W. Then, C. H. Wu, G. Walter, "Tunnel junction transistor laser," *Applied Physics Letters*, 94, 0411181 (29th Jan, 2009).

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

[4] M. Feng, Junyi Qiu, C. Y. Wang and N. Holonyak, Jr., "Tunneling Modulation of a Quantum-well Transistor Laser," *Journal of Applied Physics*, **120**, 204501–Nov. 22 (2016).