Transistor Laser Optical NOR Gate for High Speed Optical Logic Processors

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Abstract: Three-terminal transistor laser is the key element to forming a universal electro-optical NOR gate which can be developed into a compact chip-level solution for optical logic processors operating at GHz speed. We propose an optical bistable latch can be built with two universal photonic NOR gate circuits, which are implemented by the three-port tunneling junction transistor lasers (TJ-TLs).

Keywords: Optical Logic; Semiconductor Laser; Transistor Laser (TL); Vertical Cavity Transistor Laser (VCTL); Tunneling Junction Transistor Laser (TJ-TL); Optical NOR Gate.

Introduction

To fulfill the future national security and intelligence needs in this 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. Optics is capable of communicating many high bandwidth channels in parallel without suffering interference. 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, it is clear that 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.

In 2005, a new form of laser, a 3-port transistor laser (TL) shown in Fig. 1, was invented by Milton Feng and Nick Holonyak, Jr., fundamentally enables us to develop high-speed digital computation in the optical domain [1-3]. The TL possesses the advantageous characteristics of fast base spontaneous carrier lifetime in pico-second region, high differential gain, and unique 3-terminal electrical-optical characteristics for direct modulation and “read-out” of its optical parameters. These useful features allow the design of ultra-high-speed integrated optical switches that operate without the limitations of relaxation oscillations or resonance, a troublesome feature common in today’s operation of two-terminal diode lasers.

Three-Port Transistor Laser – an Integration of Quantum-Well into Heterojunction Bipolar Transistor

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}) and the diode laser (DL) invented by Hall and Holonyak (1962) operated as a 2-port device with a diode current input (I_{D}-V_{D}) and an optical output (L-I_{D}), the transistor laser (TL) is a 3-port device (an integration of quantum-well into the base 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}) [1-3].

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 (Fig. 1). Due to the thin-base of the TL, the emitter-to-collector (diffusion) transit time (\(\tau_d\)) 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 (\(\tau_0 \approx 23\) ps). Furthermore, a single QW-transistor laser (400 \(\mu\)m cavity length) was reported for a nearly resonance-free 20 GHz bandwidth operation over the base current bias range and 22 Gb/s error-free data transmission. From the bias dependent microwave modulated optical bandwidth measurement, we obtain the TL base QW e-h recombination time with a “10x fast” \(\tau_{0f}=29\) ps and a “10x higher” differential gain ~1×10^{-14} cm^2 relative to the diode laser [3-9].

We can further improve the transistor laser toward 100 GHz modulation bandwidth using a multiple QW active medium, facet coating, and enhanced optical-carrier confinement in the base to further enhance the optical gain and make possible a short cavity. With a fast recombination lifetime, the TL exhibits a carrier-photon
“resonance-free” frequency response, a reduced RIN noise, and simplified detector circuitry (not requiring the use of low-pass filters commonly seen in diode lasers).

![Diagram of a three-terminal transistor laser](image)

**Fig. 1.** Three-terminal transistor laser is the key element to forming a universal electro-optical NOR gate in which can be developed into a compact chip-level solution for optical logic processors operating at multi-deca GHz speed. The top panel shows the titled carrier distributions in the base of the TL and the bottom panel shows the NOR gate circuitry utilizing3 TLs.

**Universal Electro-Optical NOR Gate [9]**

A universal electro-optical NOR gate, based on a TJ-TL design, for all other logic functions may be constructed. The electro-optical NOR gate forms a building block for a larger optical-based network to support massive parallel computing. Moreover, all the required components for integrated circuits can be fabricated on the same epitaxial structure of light-emitting transistors, thus facilitating very large scale integration. As shown in Fig. 1,

An electro-optical universal Electro-optical NOR gate receives two signals as inputs. These signals could be in the form of optical signals, hv_{in1} and hv_{in2} or electrical signals, S (Fig. 1). It then performs a logic operation NOR on the input signals (see logic table in Fig. 2(a), and produces its result in the form of an output signal that could be either optical, hv_{out} or electrical, S. For example, if the NOR gate receives no input signal (i.e., “0”), it will produce an output signal (“1”). If there is a signal detected at the input, the NOR gate will turn off its output signal, hence outputting a logic “0”. In this case, electro-optical NOR gate will have 2^2 = 8 input states (2 optical input and 1 electrical input) for 2 optical output states (see Fig. 2(a)). If we eliminate electrical input, we will have an all-Optical NOR gate operation (set S = “0”, see Fig. 2(b)).

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**Fig. 2.** (a) An Electro-Optical NOR gate and (b) All-Optical NOR gate (set S = “0”)

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

![Diagram of a tunnel junction transistor laser](image)

**Fig. 3.** (a) TL incorporating a tunnel junction in the collector (top) An optical bistable latch (bottom panel) built with two universal photonic NOR gate circuits, which are implemented by three-port TJ-TLs (top panel).

Recently, we have shown a TL incorporating a tunnel junction in the collector (Fig. 3) [7, 9] 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) [11, 12], 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.
In conventional diode lasers, the lasing action starts only when the injection current is higher than the threshold value. On the other hand, the logic instructions (1 or 0) of digital processors propagate in terms of voltage swing, which does not suffer from capacitive loading delay and is inherently faster. Currently, there are no conventional light-emitting diodes or diode lasers that can be voltage switched and thus are unable to be incorporated in logic circuits easily. 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 laser as shown in Fig. 4. 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 \( V_{CE2} \) characteristics in Fig. 4. In addition, the corresponding TJTL collector IC-VCE2 characteristics are also illustrated in Fig. 4 with two operational regions, namely, spontaneous e-h recombination in the base QW (Black) for incoherent light output similar to LEDs and stimulated e-h recombination (Red) for coherent light output.

For an all optical NOR gate with “Logic 0” 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 shown in Fig. 5. TL0 functions as photodetector with input \( h_{vi1} \) or/and \( h_{vi2} \). 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. 5 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 \( V_{CE2} \) characteristics.

![Fig. 4. 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).](image)

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**Summary**

We propose a universal electro-optical NOR gate based on the light-emitting transistors (LETs) or tunnel junction transistor lasers (TJ-TLs), from which all other logic functions may be constructed. The optical NOR
gate thus forms a building block for a larger optical based network to support massive parallel computing. Moreover, due to its inherent transistor structure, the same device or component can be fabricated into electrical logic building blocks for computing and for all other traditional (electronics) information processing functions as well. Therein lays the uniqueness and strength of adding a “third” an optical dimension, to the present all-electronics based computing. Moreover, all the required components for integrated circuits can be fabricated on a single epitaxial structure for the light-emitting transistor, thus facilitating the integration on a very large scale and driving economies of scale à la Moore’s law.

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