Transistor Laser Optical NOR Gate for Digital Photonics

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Abstract: *The Transistor Laser (TL), a three-terminal device, holds the key to forming an optical NOR gate which can become the solution for high speed optical logic processors. In this work, we propose an optical bistable latch that can be implemented with two photonic NOR gates, which is achieved by tunneling junction transistor lasers (TJ-TL).*

Keywords: Tunneling Junction Transistor Laser (TJ-TL), Transistor laser (TL), Optical NOR Gate, Optical Logic

Introduction

With the increasing demand of high speed data transmission in data centers and cloud computing applications, a revolutionary computational technology is needed. Modern computers suffer from the RC time constants and carrier delay time [1] and hence fail to achieve better performance. To solve these problems, one solution is to replace the electrical components with optical electronic components which are capable of transmitting data at higher speeds without suffering from delays and interferences. However, there hasn't been any reported documents about optical electronics applying into digital computers to improve the performance due to the lack of optical logic processors that can provide higher bandwidths. Throughout intensive research efforts, it is clear that digital computers need to encompass the advantages of photonics for better flexibility with parallel optical processing and capability in optical input/output (I/O) [1].

In 2005, Milton Feng and Nick Holonyak Jr invented the transistor laser (TL) shown in Fig. 1, which is a three port device that can function both as a laser and as a transistor. This brand new device suggests the capability of developing high speed electronics in the optical domain as in addition to the electrical domain [1, 3]. With the unique features of the TL, such as high differential gain and faster carrier lifetime in the base, ultrahigh speed optical integrated switches can be constructed. Unlike today's diode laser (DL), the TL doesn't suffer from the electrical oscillation or resonating behavior [3].

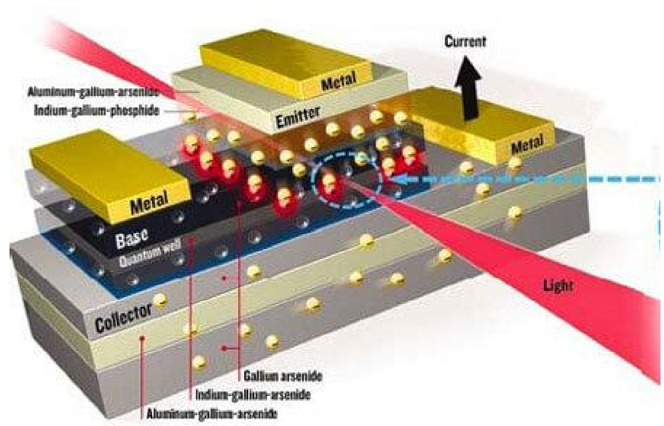

Figure 1: Cross-section view of a transistor laser [2]

Three-terminal device: Transistor Laser

In 1947, Bardeen and Brattain invented the most important device: two-port transistor with the base as input and the collector as output, which was the prototype of bipolar semiconductor triode (i.e. positive and negative charge conduction) [3]. In 1962, Nick Holonyak Jr. invented the first DL which operates as a normal two-port diode with a diode current input and an optical output. With a large amount of effort in the research of DL and the bipolar transistor, Milton Feng and Nick Holonyak Jr invented the TL in 2005 with the integration of quantum wells into the base of the bipolar transistor. The TL is a three-terminal device with the base as the electrical input ($I_B - V_{BE}$), the collector ($I_C - V_{CE}$) as the electrical output, and the coherent light emission as the optical output ($L - V_{CE}$) shown in Fig. 2 [2-4].

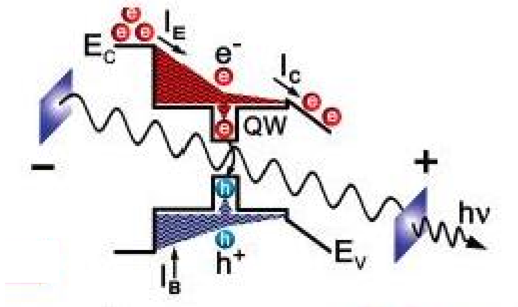

Figure 2: Energy band diagram and charge population of a quantum-well (QW) based transistor laser [3]

In contrast to the two-port DL with a slow carrier lifetime in the nanosecond range, the TL has a faster carrier lifetime by tilting the charge population and diffusing carriers across the QW base region [1] shown in Fig. 2. With the intentionally designed thin base, the transit time (τ_t) between emitter and collector can be scaled down to a few picoseconds due to the fast removing process of the slower carriers in recombination [1]. Therefore, the TL recombination lifetime in the base of the TL can be controlled to the same level as the base transit time. We have demonstrated experimentally a light-emitting transistor with a base and emitter short as a tilted charge diode can have a base recombination life time less than 23 picosecond [5]. Moreover, a single-QW based TL has been reported with 20 GHz bandwidth and a 22 Gb/s error-free data transmission [6].

We can further improve the TL modulation bandwidth by using a multiple QW active region, facet coating, and enhanced optical-carrier confinement in the base region for optical gain enhancement [1]. TL also exhibited a "resonance-free" frequency response due to its fast recombination lifetime, which also reduces the relative intensity noise (RIN) and makes the detector structure of TL much easier.

Universal electro-Optical NOR Gate with Tunnel Junction Transistor Laser

The universal electro-optical NOR gate based on a TJ-TL can be constructed as a basis for all of the logic functions. The electro-optical NOR gate receives two inputs which can be either optical signals (hν_{in1} & hν_{in2}) or electrical signals (S) shown in Fig. 3.

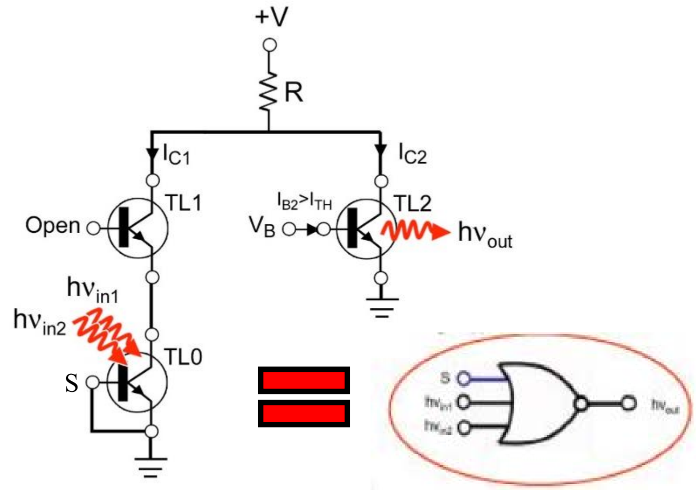

Figure 3: Universal electro-optical NOR gate circuity based on three TLs [1]

TL0 functions as a photodetector with base-emitter shorted as the NOR gate input side. TL1 acts as an active load with the base terminal open. TL2 functions as a transistor laser. The operation of the universal electro-optical NOR gate is explained below.

If the optical NOR gate receives no input signal (i.e. two "Logic 0"), then it will produce a "Logic 1" as the output signal (Fig. 4): TL0 is biased at 0.8V, but no current is drawn by the left branch due to the absence of an optical input signal; thus the collector voltage of TL2 will be solely determined by the load resistor R, which is 0.8V in this case. A fixed base current I_B = 80 mA with coherent light output of approximate 95 μW is collected under this bias condition [1], which is also marked on the optical and electrical output plots. Additionally, the spontaneous recombination curves are marked in black and stimulated recombination in red in order to specify the transition due to the laser threshold.

If there is a signal detected at the input (i.e. any of the input is a "Logic 1"), then there will be no signal at the output (i.e. the output signal will be a "Logic 0". Finite input signal on TL0 will start to draw current (I_{C1}) and raise the collector voltage of TL2 to 1.6V, for example. Figure 5 shows the corresponding collector current and optical power as V_{CE2} increases from 0.8V to 1.6V: TL2 transitions from stimulated emission to spontaneous emission and thus produces nearly no light. The drop of optical output at high collector voltage can be attributed to the decrease of coherent photon density in the optical cavity via Feng-Holonyak Intra-Cavity Photon Assisted Tunneling (FH-ICPAT) [1].

In summary, a comprehensive operation of the universal electro-optical NOR gate is shown in Table 1 with various input states and output states.

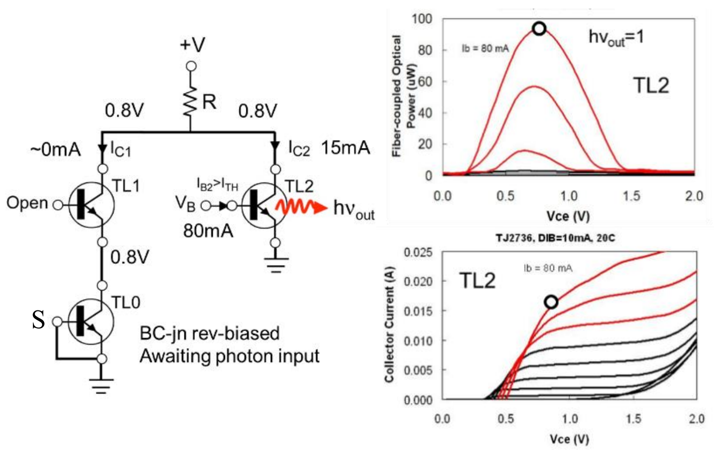

Figure 4: Optical NOR gate with “Logic 1” operation and the corresponding collector current and optical power in TL2 when V_{CE2} =0.8V [1]

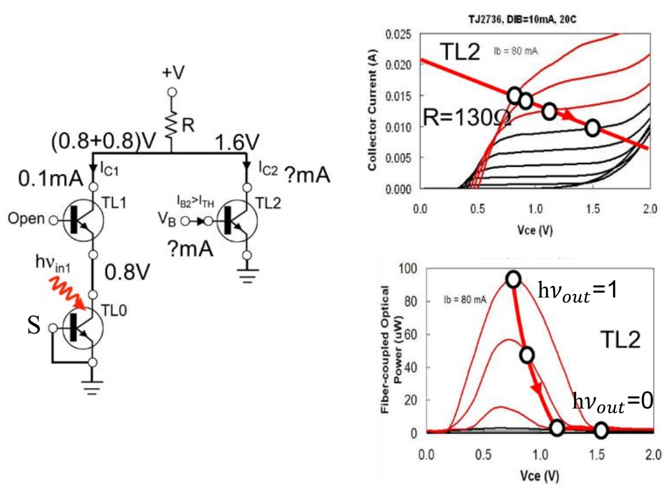

Figure 5: Optical NOR gate with “Logic 0” operation and the corresponding collector current and optical power in TL2 when V_{CE2} =1.6V [1]

Table 1: Operation of an electro-optical NOR gate [1]

$h\nu_{in1}$	$h\nu_{in2}$	S	$h\nu_{out}$
0	0	0	1
1	0	0	0
0	1	0	0
1	1	0	0
0	0	1	0
1	0	1	0
0	1	1	0
1	1	1	0

Tunnel Junction Transistor Laser and Bistable Latch

A TL incorporating a tunnel junction has been reported recently [7, 8], which makes the voltage modulation possible by changing the bias voltage on the collector as shown in Fig. 6. I_E is the emitter current (minority current in base), I_B is the re-supply of hole current, and I_c is the collector current consisting of I_{rT} (re-supply of hole via the direct tunneling of electrons in base-collector junction) , I_t (minority current of injected electrons that don’t recombine in the base region) and I_{paT} which is the current related to the photon absorption in the collector with the ICPAT when the base-collector junction reaches sufficient reverse bias [8]. This tunnel junction functions as an additional supply of holes to the base [1], which increases the flexibility of TL in logic circuits.

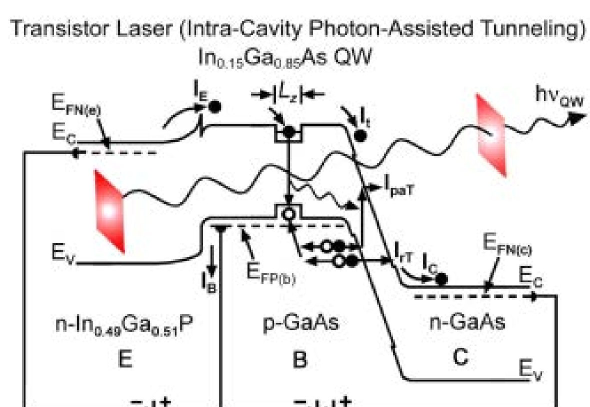

Figure 6: Schematic energy band diagram of a tunnel junction in the collector of TL [8]

The switching of TL2 between "Logic 0" and "Logic 1" is determined by the voltage drop in the collector by the tunneling photon modulation with the ICPAT, which is a unique characteristic of TJ-TL [1]. Therefore, we have designed the bistable latch based on this characteristic with four different states: (a) All-optical bistable latch (shown in Table 2), (b) electrical-in, optical-out bistable latch, (c) optical-in, electrical-out bistable latch and (d) all electrical-in bistable latch [1]. The circuitry of this bistable latch is shown in Fig. 7.

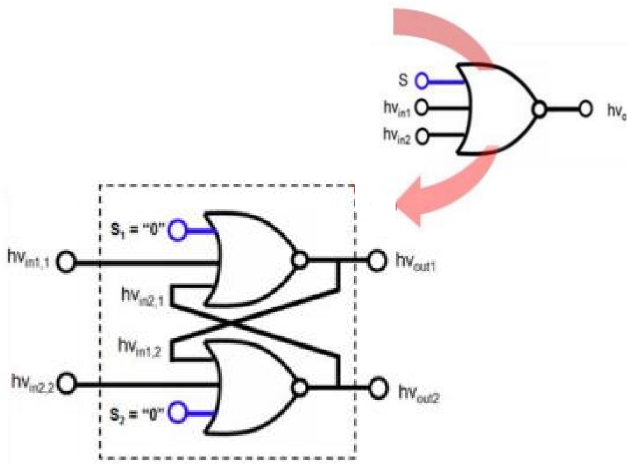

Figure 7: Optical bistable latch circuity

Table 2: Logic table for all-optical bistable latch [1]

$hv_{in1,1}$	$hv_{in1,2}$	hv_{out1}	hv_{out2}
0	0	No change	No change
0	1	0	1
1	0	1	0
1	1	Forbidden	Forbidden

Summary

In this work we proposed a universal electro-optical NOR gate based on the TJ-TL with the comprehensive and possible logic operation that this powerful device can achieve. This three-terminal device can form the building block of a bistable latch which is indispensable in today's computer technology and Random Access Memory (RAM) devices. With the aid of this device, it is possible to fabricate all circuit components on the same epitaxial structure, significantly improve performance, and support massive computing applications.

Acknowledgements

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