Optical NOR Gate Transistor Laser Integrated Circuit

Ardy Winoto, Junyi Qiu, Dufei Wu, and Milton Feng
Micro and Nanotechnology Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign
208 N. Wright St., Urbana, IL 61801, U.S.A.
mfeng@illinois.edu

Abstract: An optical NOR gate has been demonstrated monolithically in a transistor laser structure using voltage modulation of the light output. The NOR gate can receive multiple optical input signals and produces the corresponding light output.© 2019 The Author(s)
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1. Introduction

The development of monolithic optical logic processors has been hindered by the lack of an efficient, compact optical logic gate as a building block. Previous attempts to realize a monolithic optical logic gate include those based on optical interference phenomena in waveguides using microring resonators, semiconductor optical amplifiers (SOAs), electro-absorption modulators (EAMs), and Mach-Zender modulators [1, 2]. The major disadvantage of these devices is their large size, which limits their integration potential. Semiconductor-based optical logic gates have also been demonstrated. A laser-photothyristor implementation [3] achieved monolithic logic operation, but has extremely slow switching speed. Another demonstration is a cascadable laser logic device [5] which uses a diode laser grown on a phototransistor, creating a p-i-n-p-n structure. The cascadable laser logic device suffers from a very complex layer structure, resulting in extremely complex device fabrication that is not suitable for large-scale integration. The transistor laser, invented by Feng and Holonyak [6], combines the intrinsic switching property of a bipolar transistor and the coherent light output of a laser in a single device, making it uniquely suited for electro-optical integration. Unlike a diode laser, the transistor laser light output can be modulated without an external driver, which greatly reduces the complexity of the transmitter circuitry. Optical modulation via intra-cavity photon-assisted tunneling (ICPAT) [7] allows for efficient and potentially high-speed voltage-based switching. The transistor laser has the potential to act as a unifying technology to an optical integrated circuit similar to how the transistor is to an electrical integrated circuit. In this work, we fabricated and demonstrated the first transistor laser-based integrated circuit and the first optical logic gate using transistor laser technology.

2. Light-emitting Transistor Optical NOR Gate

The use of the transistor laser for optical logic processing has been previously proposed [8]. A NOR gate structure was chosen to demonstrate the logic processing functionality of a transistor laser integrated circuit due to its universal logic nature as well as relatively simple structure. The circuit implementation of the optical NOR gate is shown in figure 1(a), which contains three devices monolithically integrated in the transistor laser epitaxial structure. TL0 acts as a photodiode which senses optical inputs, TL1 acts as an active load, and TL2 is a regular transistor laser that acts as the output stage and is biased to be always on. When an optical input is present on TL0, the resulting photocurrent sets the collector current IC1 of the left branch, inducing a nonzero 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. Due to the dependence of transistor light output on the base-collector voltage through ICPAT, the increase in collector voltage will lead to a light output reduction in TL2.

Figure 1(b) shows the device level implementation of the optical NOR gate based on previously reported transistor laser work [9]. TL0 is implemented as a vertical photodiode in the base-collector junction of the transistor laser epitaxial structure. The optical input is applied using a fiber probe and an external modular laser, while the electrical inputs are provided using DC and GSG probes. Figure 2(b) shows the L-I-V curves of the output transistor laser TL2 under normal operation. TL2 produces low light output due to its spontaneous emission operation, acting as a light-emitting transistor as a result of excess resistances incurred in the integration process. Regardless, the ICPAT characteristics of light modulation are still present and the light output shows a strong dependence on the collector-emitter voltage. Figure 2(b) shows the logic diagram of the optical NOR gate in the case of a single, manually switched optical input. Note that the NOR operation can be implemented simply by coupling two light sources into the optical NOR gate input aperture.

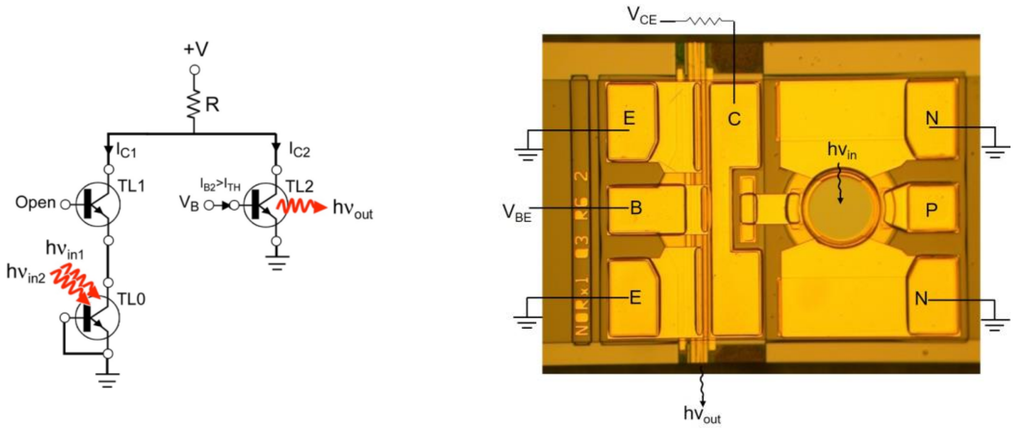

Figure 1. (a) Circuit diagram for the transistor laser optical NOR gate, including TL2 as a regular transistor laser, TL1 as an active load, and TL0 as a photodiode. (b) Device implementation of the transistor laser optical NOR gate with a vertical photoreceiver, overlaid with the probing arrangement.

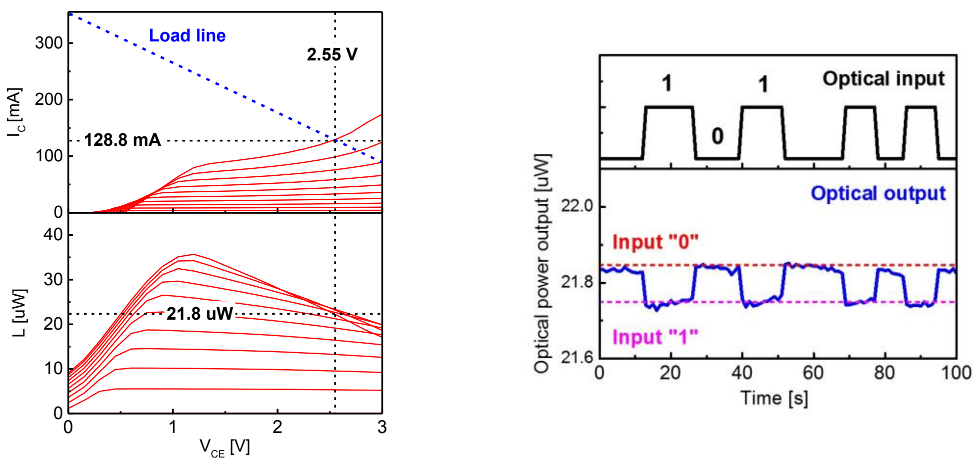

Figure 2. (a) L-I-V curves of TL2 showing light-emitting transistor behavior. The blue line indicates the load line set by the voltage supply (V = 4 V) and the load resistor (R = 11.3 Ω). (b) Logic timing diagram for the optical NOR gate for a single input case.

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