Integrated Photonics of Transistor Laser, Detector and Active Load for All Optical NOR Gate

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Abstract: *The transistor laser is a promising candidate for high-speed integrated optoelectronics for its capability to operate under both base current modulation and collector tunneling modulation simultaneously, which fundamentally enables the monolithic integration of electrical and optical signal processing on the device level. This work demonstrates one of such applications by building an optical-to-optical NOR gate with the transistor laser in an integrated form.*

I. Introduction

The transistor laser (TL) invented by Milton Feng and Nick Holonyak, Jr. [1,2] inherits the benefits from heterojunction bipolar transistor (HBT) with quantum-wells inserted in the base for faster recombination process and coherent optical output. Different from the typical diode laser, the TL has a tilted charge profile such that instead of waiting carriers to "pile-up" for recombination, the carriers will be swept by the electric field towards the collector. Therefore, the recombination time has been reduced from nanosecond range as in the typical diode laser to picosecond range in the TL, resulting a resonance-free frequency response and high modulation bandwidth [3]. Apart from the fast recombination, the TL's four-port functionality is also a unique trait as opposed to the typical two-port operation of diode lasers. The four-port operation of the TL is realized by the intra-cavity photon-assisted tunneling (ICPAT) in the collector junction acting as a built-in voltage-controlled optical absorber as well as a source for carrier re-supply in the base and collector current output, which makes the direct voltage modulation possible in addition to the common current-injection modulation from the base [3].

Compared with current diode laser process, the TL not only can be modulated without any external modulators or drivers, reducing the complexity of the circuitry, but also can be fabricated monolithically for both transmitter and receiver on the same substrate, which is essential for integration. The receiver can be implemented by using an additional intrinsic layer or the base-collector junction of the TL. An example of the wafer-level integration for both transmitter and receiver (transceiver) is shown in Fig. 1 [5]. Aside from the typical application in optical data transmission, the TL has been proposed for an optical NOR gate logic [4]. In this work, we report the fabrication and the characterization of an all-optical NOR gate based on TL.

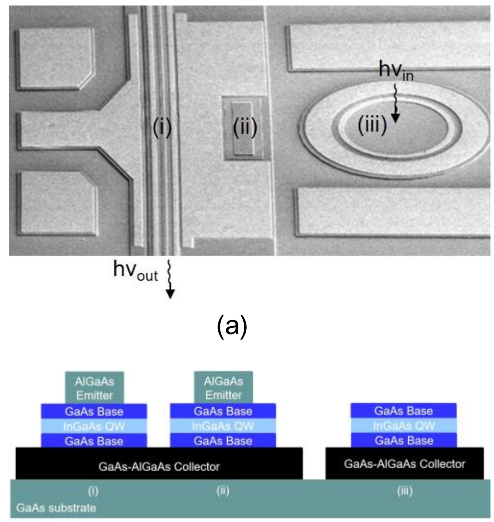

Fig. 1. Top view (a) and cross-section diagram (b) of a transistor laser integrated circuit containing a transistor laser with an optical cavity and cleaved facets (i), an HBT without an optical cavity (ii), and a vertical p-i-n photodiode (iii).

II. Theory of Operation

The circuitry of an all-optical TL-based NOR gate is shown in Fig 2. TL2 is a regular TL similar as the one in previous work [5]. TL1 is an HBT with an open base configuration, acting as an active load to increase the output impedance of the left half. TL0 is a P-i-N photodetector formed with the base-collector junction of transistor laser. The functionality of an optical NOR gate is explained as follows: when there is no optical input at TL0, TL2 will be in the lasing state with a constant optical output ("Logic 1") at an appropriate base current bias level [4]; the inverted topology of "Logic 0" is realized when there is one or multiple optical inputs detected at TL0, such that the increased collector-emitter voltage at TL2 shifts the operation point of the TL2 along the load line, causing the laser light output to decrease. The operation of the NOR gate is simulated with Keysight ADS and shown in Fig. 3. Theoretically, the optical NOR gate design can function more than two inputs since each additional input only serves to increase the collector-emitter voltage at TL2 and therefore the optical output at TL2 diminishes [5]. The threshold of logic ‘0’ should be set at the output level of a single active input.

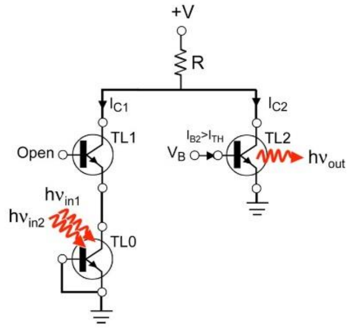

Fig. 2. Circuit diagram of a transistor based optical NOR gate.

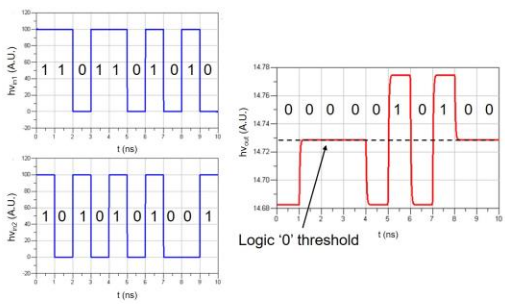

Fig. 3. Simulated logic diagram for a two-input optical NOR gate at 1 Gb/s.

III. Fabrication Process

The TL epitaxial structure is grown by MOCVD on a semi-insulating GaAs substrate. The emitter is formed with the n-type AlGaAs and the base of the TL is formed with p-type GaAs. There is an InGaAs quantum-well inside the base to promote recombination process. The device layout and the lateral cross-section view are shown in Fig. 4. The metal interconnect is placed after planarization with benzocyclobutane (BCB) and the double via process formed by dry-etching. After the top metal has been established, the wafer is thinned down to 150 µm and cleaved into stripes to form the facets of edge-emitting lasers. Each stripe is then bonded with indium to a copper substrate for testing [5].

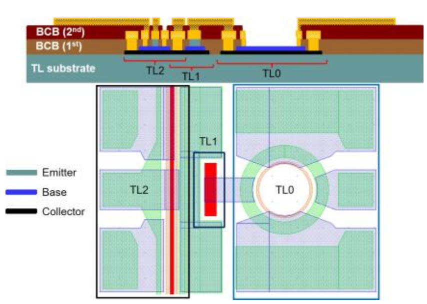

Fig. 4. Lateral cross-section and top view diagrams of the transistor laser all optical NOR gate.

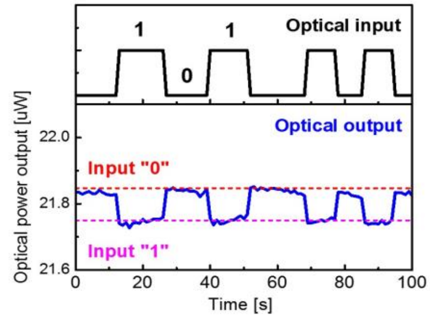

Fig. 5. Logic timing diagram for the optical NOR gate.

IV. Characterization

The logic functionality of the TL- based optical NOR gate is performed with a base current of 50 mA as input to maximize the optical output. The voltage supply is set at 4V with the external resistor of 11.3 Ω, resulting a collector-emitter voltage of 2.3V at TL2. The optical input to the TL0 is coupled from an external modular laser and the responsivity has been characterized as 0.0346 A/W. After the signal is coupled into TL0 and switched on and off to provide a square input signal, the generated optical output at TL2 is shown in the blue line in Fig.5 [5]. It should be noted that in this case the NOR gate acts like an inverter due to the single input. The functionality of NOR gate can be realized by feeding a multi-level optical input signal or two optical inputs. The threshold of logic 0 is 21.75 µW and that of logic 1 is 21.85 µW.

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