# GHz Modulation Enabled Using Large Extinction Ratio Waveguide-Modulator Integrated with InGaN Laser Diode

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***Abstract*—A 404-nm emitting InGaN-based laser diode with integrated-waveguide-modulator showing a large extinction ratio of 11.3 dB was demonstrated on semipolar $(20\bar{2}\bar{1})$ plane GaN substrate. The device shows a low modulation voltage of -2.5V and ~ GHz -3 dB bandwidth, enabling 1.7 Gbps data transmission.**

***Keywords— InGaN; waveguide modulator; electroabsorption absorber; laser diode; visible light communication.***

## I. INTRODUCTION

InGaN-based violet-emitting laser diodes (LDs) have attracted increasing research attention due to its application for high color rendering index white lighting system [1], high-speed visible light communication [2] as well as avoiding the health-related concerns associated with blue laser diodes [3]. Compared to the direct modulation of LDs, the modulation utilizing integrated electroabsorption modulator (EAM) is advantageous due to low power consumption and suppression of transient heating [4, 5]. This paper presents the waveguide EAM-integrated LD emitting at 404 nm, where the EAM and LD are fabricated using the same InGaN/GaN quantum well structure, grown on semipolar $(20\bar{2}\bar{1})$ plane GaN substrate. A large extinction ratio of 11.3 dB is measured in our device with a modulation voltage as low as -2.5 V to achieve On/Off switching, which are the best results achieved in III-nitride system to the best of our knowledge. This is attributed to the small polarization field in the device grown on semipolar substrates. By modulating the EAM-integrated LD, a -3 dB bandwidth of ~1GHz, which is limited by the photodetector, and data rate of 1.7 Gbps is measured, suggesting it to be a novel platform for visible light communications.

## II. RESULTS AND DISCUSSIONS

The schematic of the EAM-integrated LD fabricated is shown in Fig. 1(a), which is a three-terminal device consisting of 7.5-µm-wide ridge waveguide. The 100-µm-long integrated modulator and the 1390-µm-long gain section were optically coupled but electrically isolated (153 kΩ resistance was measured between the two sections). The device was tested using Keithley 2520 diode laser tester and Keithley 2400 source-measure unit with calibrated Si photodetector (PD). The spectrum was measured using Ocean Optics HR4000 spectrometer. For bandwidth measurement and data transmission using on-off keying (OOK) modulation scheme, an Agilent E8361C network analyzer, an Agilent N4903B J-BERT, an Agilent DCA-86100C digital communication analyzer, and a Menlo Systems APD-210 Si avalanche PD (APD) were used in the setup. At 700-mA injection current in the gain section, the EAM-integrated LD lased at 404 nm as shown in Fig. 1(b).

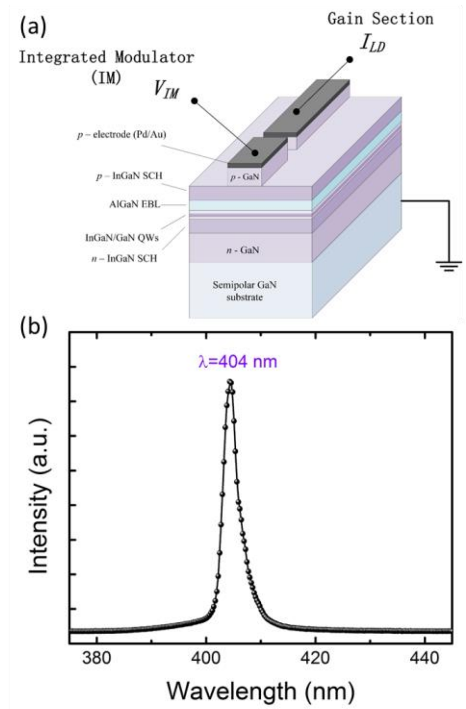


Fig. 1. (a) Schematic of the EAM-integrated LD device structure. (b) Lasing spectrum of the EAM-integrated LD.

Fig. 2(a) shows the optical power *vs.* injected current in the gain section (*L-I*) and the characteristics of the EAM-integrated LD under the applied bias from 0 V to -3 V. The current *vs.* voltage (*I-V*) relation can be found in the inset of Fig. 2(a). Without modulation bias ($V_{IM}$=0), the device shows a threshold current ($I_{th}$) of 590 mA, and an optical power of 5.2 mW at 650 mA in the gain region ($I_{LD}$=1.1×$I_{th}$). With increasing $|V_{IM}|$, a decreasing optical power and increasing $I_{th}$ were achieved owing to the quantum-confined Stark effect induced electroabsorption effect [5]. The optical power of the EAM-integrated LD was 5.2 mW, 2.7 mW, 1.3 mW, 0.56 mW and 0.38 mW at $V_{IM}$ = 0V, -1 V, -1.5 V, -2 V, -2.5 V, respectively, as shown in Fig. 2(b), suggesting the strong $V_{IM}$-dependence in optical power. The lasing action was suppressed at $|V_{IM}|$ > 2 V, representing the *off* state at $I_{LD}$ = 650 mA. The maximum optical power was at $|V_{IM}|$

= 0V, which is the *on* state. A large extinction ratio ($R_{on/off}$=$P_{ON}$/$P_{OFF}$) of 13.53 (~ 11.3 dB), and relatively small modulation bias of 0V/-2.5V were measured in our EAM-integrated LD, where a high modulation efficiency of 4.5 dB/V was derived. This is significantly higher than that of c-plane modulator (~ 1.1 dB/V).

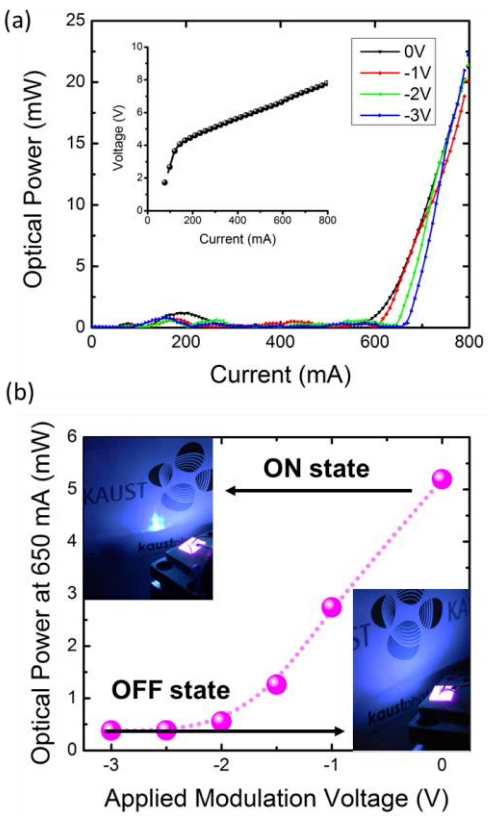


Fig. 2. (a) Optical power *vs.* injection current ($I_{LD}$) of the EAM-integrated LD at different modulation bias ($V_{IM}$). Inset: current vs. voltage of the device. (b). Optical power at 650 mA vs. $V_{IM}$. Inset: photos of the device emissions at *ON* and *OFF* states.

To demonstrate the utilization of EAM-integrated LD for visible light communications, the small signal modulation measurement was performed by applying -10 dBm AC signal to the EAM while the gain section was driven at constant $I_{LD}$ of 650 mA). A -3dB bandwidth of ~ 1GHz was measured as shown in Fig. 3(a) with $V_{IM}$ = -1 V. The frequency response is limited by the 1-GHz bandwidth of the APD. Nonetheless, the feasibility of utilizing EAM-integrated LD for data transmission has been confirmed. Subsequently, the EAM-integrated LD was used to transmit a pseudorandom binary sequence (PRBS $2^{10}$-1) data stream using OOK modulation scheme. A clear open-eye diagram at 1-Gbps data rate (inset in Fig. 3(a)) was observed, and a relatively low bit-error rate (BER) of $1.1\times10^{-6}$ was measured. A high data rate of 1.7 Gbps using the EAM-integrated LD was achieved (Fig. 3(b)) with BER of $3.1\times10^{-3}$, still passing the forward error correction (FEC) limit ($3.8\times10^{-3}$). The data rate could be further improved by further optimizing the system, and employing complex modulation scheme, such as orthogonal frequency-division multiplexing.

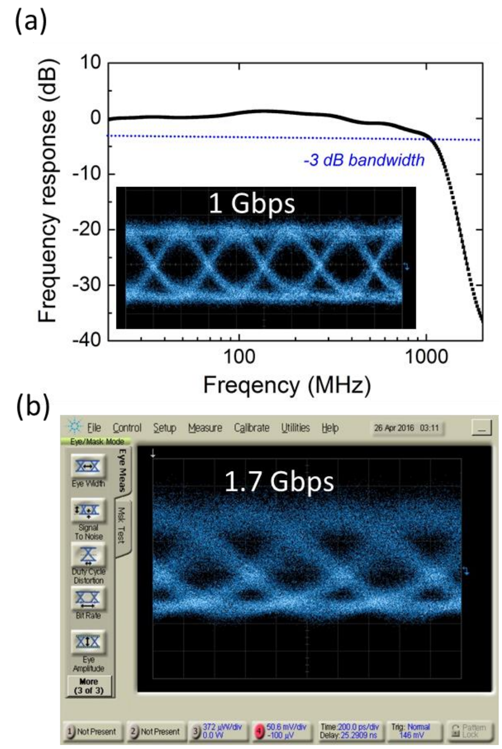


Fig. 3. (a). Frequency response of the EAM-integrated LD under $I_{LD}$ of 650 mA and $V_{IM}$ of -1V. Inset: Eye diagram of 1 Gbps data rate using OOK modulation. (b). Eye diagram of 1.7 Gbps data rate using OOK modulation.

## III. Conclusions

The InGaN/GaN quantum well based electroabsorption modulator integrated with laser diode showing large extinction ratio of 11.3 dB and high modulation efficiency of 4.5 dB/V was demonstrated. The violet-emitting EAM-integrated LD has a -3 dB bandwidth of ~ 1 GHz, enabling 1.7 Gbps data rate using OOK modulation scheme. Our results show that the EAM-integrated LD on semipolar plane GaN substrates are favorable for low power consumption visible light communications.

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