Low Modulation Bias InGaN-based Integrated EA-Modulator-Laser on Semipolar GaN Substrate

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I. INTRODUCTION

The development of InGaN based laser diodes (LDs) [1] for visible light communication [2] has recently attracted increasing attention. The common feature of the devices demonstrated so far has been the implementation of direct current modulation of laser diodes [3-5]. In this work, we reported an alternate modulation approach based on seamless, monolithic integration of optical modulator with laser diode. There are several potential benefits of this approach over the direct modulation of LDs: (1) suppression the deleterious transient heating [6]; (2) reduction of dissipated switching power [7]; and (3) smaller capacitance [8]. As the electroabsorption-modulator (EAM) can be fabricated using the same InGaN/GaN quantum well (QW) structure as the laser diode, subsequent epitaxy regrowth is not required.

In this paper, we demonstrated the first blue-emitting integrated electroabsorption-modulator-laser (IML) grown on semipolar (202T) GaN substrate. Due to a smaller polarization field in InGaN/GaN quantum-well device grown on semipolar substrate, we demonstrated that 0 V / -3.5 V modulation biases are sufficient for On/Off switching operation, which is half of the bias required for the modulator grown on c-plane substrate.

II. EXPERIMENTS

The InGaN/GaN QW based IML is a three-terminal device consisted of reverse-biased integrated modulator section and forward-biased gain section (see Fig. 1) grown using metalorganic chemical vapor deposition (MOCVD). The IML is made of 2μm-wide ridge waveguide with 100 μm integrated modulator (IM) and 1100 μm gain sections. Both sections are optically coupled but electrically separated (22 kΩ resistance between the two sections). The device was tested using Keithley 2520 diode laser testing system with calibrated Si photodetector and integrating sphere from Labsphere. The small signal modulation characteristics were measured using Agilent E8361C network analyzer and Menlo Systems APD 210 Si avalanche photodetector.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the optical output power vs. the injection current in the gain region (L-I) characteristics for the IML under different bias voltage in the modulator section (VIM from 0 V to -3.7 V). Without any modulation bias (VIM = 0 V), the IML shows a threshold current of Fig. 2. Plot of: (a) optical power vs. injection current (L-I) of IML with varying bias voltage on IM. The optical power at 468 mA (1.2 Ith) in the gain region is indicated, and (b) optical power at 468 mA vs. the absolute modulation bias voltage, |VIM|.

Fig. 1. Schematic diagram of integrated electroabsorption-modulator-laser (IML) on semipolar (202T) GaN substrate.
amplitude modulation effect. When \( |V_{\text{optical power}}| \) is evident in Fig. 2(b), indicating the \( I_{\text{LD}} = 468 \) mA, the IML exhibited an significant when \( I \) was limited to 500 mA as the thermal roll-over became output power under DC operation. The operating current |V| was \( 0.8 \) mW, \( 3.7 \) mW, and \( 1.4 \) mW at \( V_{\text{IM}} = -1 \) V, \(-2\) V, \(-3\) V, and \(-3.5\) V, respectively. The strong \( V_{\text{IM}} \)-dependence in optical power is evident in Fig. 2(b), indicating the amplitude modulation effect. When \( |V_{\text{IM}}| > 3.5 \) V, the lasing was suppressed at \( I_{\text{LD}} = 468 \) mA, which representing the Off state. The IML has its maximum emission power at \( V_{\text{IM}} = 0 \) V, which is the On state. At \( I_{\text{LD}} = 468 \) mA, the IML exhibited an On/Off ratio (\( P_{\text{ON}}/P_{\text{OFF}} \)) of 6.5 (~8.1 dB) with a relatively small bias of 0 / -3.5V, compared to ~ 7 V required in c-plane modulators [7].

To study the electroabsorption response in semipolar (2021) InGaN/GaN QWs based integrated modulator, the modal absorption was measured using segmented contact method [9]. Figure 3 shows the changes in modal absorption with \( V_{\text{IM}} \) varied from -1 V to -3.5 V, which were calculated by subtracting the measured unbiased absorption spectrum from that of the biased absorption spectrum. The change is due to the applied external field on IM partially cancels the built-in polarization-induced electric fields in the active region, thereby increasing the absorption with increasing \( V_{\text{IM}} \). The measured change in modal absorption at the IM section at \( V_{\text{IM}} = -3.5 \) V is ~27 cm\(^{-1}\), which corresponds to an absorption coefficient change of ~600 cm\(^{-1}\) at the lasing wavelength. Thus, the significant change in absorption coefficient in IM region in response to modulation bias is effective for modulating the optical output power of IML.

For a proof-of-concept demonstration of AC modulation, we performed the small signal modulation measurement by applying -10 dBm AC signal to the integrated modulator while pumping the gain region with a constant driving current (470 mA). A -3dB bandwidth of ~0.98 GHz was measured in the IML with \( |V_{\text{IM}}| = 3 \) V (see Fig. 4). The frequency response is limited by the bandwidth of the photodetector. Nevertheless, our demonstration proves the feasibility of using IML for data transmission.

### IV. CONCLUSIONS

In summary, we demonstrated the monolithic integration of electroabsorption modulator with laser diode and measured DC and AC modulation characteristics of the device, which is grown on (2021) plane GaN substrate. By alternating the modulation voltage at -3.5 V and 0 V, we achieve the laser output power of <1.5 mW to >9 mW, respectively, leading to ~8.1 dB On/Off ratio. Our results clearly show that a low power consumption modulator can be achieved with semipolar EA-modulator compared to that of the c-plane devices.

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