Spectral characteristics of a 1.3-µm npn-AlGaInAs/InP transistor laser under various operating conditions

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Abstract: The spectral characteristics of a 1.3-µm npn-AlGaInAs/InP transistor laser were studied under various collector–base voltages and emitter currents. The result shows that the peak wavelength shifts as a function of the output power resulting from voltage and current controls exhibited contrasting behavior under a continuous-wave operation.

Keywords: semiconductor laser, transistor laser, AlGaInAs/InP

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

1 Introduction

In optical fiber communications, especially for WDM transmission, wavelength stabilization of the light source while controlling the output power is the most critical point. In conventional laser diodes (LDs), output power control can be realized by changing the injection current; however, this process causes a wavelength shift because of Joule heating [1, 2]. As a result, conventional LDs cannot control the output power while maintaining the wavelength. Therefore, for such applications, recent light sources such as tunable lasers have integrated semiconductor optical amplifiers to independently control the output power [3]. In contrast, another approach is to install built-in output power control function with no Joule heating in the LD itself. One of the candidates for such function is the transistor laser (TL), which is based on a heterojunction bipolar transistor with an active layer at its base region [4]. Owing to its three-terminal structure, the TL can achieve output power control with different spectral characteristics compared with conventional lasers by applying a collector–base voltage. In addition, the TL has the potential to break the modulation speed limitations inherent in conventional LDs because shorter carrier recovery times can be achieved [5, 6, 7, 8, 9, 10]. Until now, several studies on the 0.98-µm TLs have been conducted [11, 12, 13]. In our previous reports, we successfully achieved the first room-temperature continuous-wave (RT-CW) operation at longer wavelengths as well as the transistor characterization of a pnp [14] and an npn TL emitting at the 1.3-µm wavelength using an AlGaInAs/InP material system [15].

In the present paper, we will report the study on the spectral characteristics of 1.3-µm npn-AlGaInAs/InP TLs under various collector–base voltages. Comparison with those under various emitter currents is also presented.

2 Device structure

The schematic structure of the fabricated npn-TL in this study is shown in Fig. 1. The initial wafer was grown on a (100) n-InP substrate using an organo-metallic
vapor phase epitaxy technique. The initial wafer consisted of an n-AlGaInAs emitter, five fully strain-compensated AlGaInAs quantum wells [(QWs) with $\lambda_g = 1.3$ $\mu$m, 5-nm-thick well, and 10-nm-thick barrier], a p-AlGaInAs (with $\lambda_g = 1.07$ $\mu$m and 80-nm thick), and a p-GaInAsP (with $\lambda_g = 1.17$ $\mu$m and 30-nm thick). Although we intentionally did not dope the QWs, Zn diffusion was confirmed to make a p-type transistor base. A buried hetero (BH) structure with n/p/n/p-InP current-blocking layers was formed by wet etching and selective regrowth [15]. After the BH structure formation, a 200-nm-thick p-GaInAsP base layer ($E_g = 1.06$ eV; $N_A = 1 \times 10^{18}$ cm$^{-3}$), an n-InP collector layer (2000-nm thick), an n$^+$-GaInAs collector contact layer, (50-nm thick; $N_D = 1 \times 10^{19}$ cm$^{-3}$), and a p$^+$-GaInAs base contact layer (50-nm thick; $N_A = 1 \times 10^{19}$ cm$^{-3}$) were formed at the side through several regrowth steps. The collector and base mesas were formed using RIE and wet etching. Finally, the collector, base, and emitter (backside) electrodes were formed by evaporating Ti/Au (25 nm/200 nm) onto the device. The details of the fabrication process can be found in our previous reports [15, 16]. Laser cavities were formed by cleavage with no high-reflection coating.

![Fig. 1. Structure of an npn-AlGaInAs/InP TL.](image)

### 3 Measurement

Fig. 2 shows the current–output power ($I$–$L$) characteristics of the TL with a common–base (CB) configuration under a CW condition at a stage temperature of 10°C. The cavity length and the stripe width were 1000 and 1.5 $\mu$m, respectively. A threshold emitter current of 40 mA (current density $J_{th} = 2.7$ kA/cm$^2$) and a differential quantum efficiency of 7% from both facets were obtained. By applying collector–base voltage $V_{CB}$, both an increase in the threshold current and a decrease in the output power were observed because of the optical absorption at the p-GaInAsP base layer due to the Franz–Keldysh and the Early effects, which increased the collector current. Thus, a higher emitter current was needed to boost the base current to reach the threshold [17]. Therefore, the output power can be controlled by controlling $V_{CB}$ without changing the emitter current, which changes the amount of Joule heating. The TLs used in the current study had a very small electrical amplification ($\beta < 1$; therefore, the devices used in the experiment were not actually “transistors” in terms of electrical characteristics although they have “transistor” structures) by having a
relatively thick p-GaInAsP base layer for the purpose of output power control without changing the amount of Joule heating. Using this device, the lasing spectra were measured by varying both emitter current $I_E$ and $V_{CB}$. Because the device had a FP cavity structure and showed a multi-longitudinal-mode operation, we traced one peak mode.

Figs. 3 and 4 show the lasing wavelength as a function of $I_E$ with various $V_{CB}$ values under CW and pulsed operations (pulse width = 1 µs and repetition = 1 kHz), respectively. Under the CW operation (Fig. 3), the peak lasing wavelength was red shifted by increasing $I_E$ because of the Joule heating, which is the same as that of conventional LDs. On the other hand, under the pulsed operation (Fig. 4), no wavelength shift was observed by increasing $I_E$, whereas a slight red shift was observed by increasing $V_{CB}$, which may be attributed to either the refractive-index change or large quantum-confined Stark effect (QCSE), as discussed later.

Next, the lasing wavelength as a function of $V_{CB}$ with various emitter currents was measured under CW and pulsed operations, as shown in Figs. 5 and 6, respectively. Fig. 5 shows that a red shift was observed by increasing $I_E$ under the CW operation because of the Joule heating, as mentioned before. The peak lasing wavelength of the TL was red shifted as $V_{CB}$ was increased even under the pulsed operation, which means that the shift was not caused by Joule heating.
Although the reason for this phenomenon is still under investigation, this phenomenon could be considered as either a refractive-index change in the p-GaInAsP by $V_{CB}$ or a large QCSE in the QW active region that exceeds the amount of carrier screening effect.

Finally, Fig. 7 shows the peak lasing wavelength as a function of the output power under the CW operation. The red squares indicate the output power.
controlled by $V_{CB}$ with a fixed $I_E$ of 80 mA. The blue diamonds indicate the output power controlled by $I_E$ with a fixed $V_{CB}$ of 0.5 V. A difference between the two measurements is evident. When the output power was increased by $I_E$, the temperature rise in the device caused a red shift, as mentioned earlier. On the contrary, the lasing wavelength of the TL was blue shifted when the output power was increased by $V_{CB}$.

From this result, the combination of $V_{CB}$ and $I_E$ controls can achieve output power control without any wavelength change. We are currently investigating a structure that achieves no-wavelength-shift output power control by voltage modulation only.

4 Conclusion

In this study, we experimentally investigated the lasing wavelength behavior of a 1.3-µm npn-AlGaInAs/InP TL by varying the collector–base voltage and emitter current. The results showed contrasting wavelength-shift behavior between these two operating conditions under a CW operation and revealed that output power control by the collector–base voltage can be possible without Joule heating in the TL that uses this material system.

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