A 46-GHz DFB+R Laser Utilizing Detuned-Loading and Photon-Photon Resonance Effects for 6G Data Center Networks

Younghoon Kim
Photonics/Wireless Devices research Division,
Electronics and Telecommunications Research Institute,
218 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
yh1125@etri.re.kr

Young-Tak Han
Photonics/Wireless Devices research Division,
Electronics and Telecommunications Research Institute,
218 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
frenclin@etri.re.kr

Seok Jun Yun
Photonics/Wireless Devices research Division,
Electronics and Telecommunications Research Institute,
218 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
yunseokjun@etri.re.kr

Sang-Ho Park
Photonics/Wireless Devices research Division,
Electronics and Telecommunications Research Institute,
218 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
shpark@etri.re.kr

Dong-Hun Lee
Photonics/Wireless Devices research Division,
Electronics and Telecommunications Research Institute,
218 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
dhlee@etri.re.kr

***Abstract*— We report on the distributed feedback (DFB) + R laser that employs an integrated passive waveguide and a 3 % reflectivity coating on the front facet to induced the detuned-loading and photon-photon resonance (PPR) effects. Our device exhibits a 3-dB electro/optical (E/O) bandwidth of around 46 GHz at 25 °C, supporting the transmission of PAM-4 signals beyond 100 Gbps.**

Index Terms*— *6G, intra data center, optical communication, directly modulated laser, photon-photon resonance

I. INTRODUCTION

As 6G communication technologies rapidly evolve, there is an unprecedented demand for wireless capacity with high reliability, low latency, and massive data transmission rates. This includes the short-packet and detection-based Ultra-Reliable Low Latency Communication (URLLC) services which served as a foundation for the initial deployment of 5G networks. In response to these growing demands, the transmission capacity of data center networks is undergoing an explosive expansion. This is largely because a vast majority of the data traffic generated by 5G and future 6G networks must be processed, stored, and distributed by these powerful data hubs. To accommodate this dramatic increase in data throughput, there is an urgent need for the development of next-generation optical modules supporting data rates of 800-Gbps and 1.6-Tbps speeds.

In response to this requirement, the industry has recently begun a standardization effort, with the 800G-FR4 Multi-Source Agreement (MSA) having already released specifications for 800G optical modules, which adopt a 4 × 200-Gbps/lane optical interface based on 112.5-Gbaud PAM4 modulation [1,2]. Furthermore, the IEEE 802.3dj task force is actively considering a standard for 1.6-Tbps Ethernet for distances ranging from 0.5 km to 2 km, proposing the use of 106.25-Gbaud PAM4 signals [3].

Accommodating the rapidly increasing data traffic requires the implementation of high-speed optical sources with large modulation bandwidths and advanced performance characteristics. Various high-speed intensity modulation schemes have been demonstrated, including electro-absorption modulator integrated laser (EML) [4-7], membrane lasers [8,9], and directly modulated laser (DML) [10,11]. Among these candidates, DMLs are particularly promising due to their simple fabrication, low power consumption, compactness, and cost-efficiency. Owing to these advantages, DMLs are regarded as strong candidates for utilization in next-generation high-performance data centers.

To further enhance the modulation bandwidth, the detuned loading effect [12,13] and photon–photon resonance (PPR) [14,15] have been extensively researched. To induce these effects, DML structures integrating passive waveguides or distributed Bragg reflectors (DBRs) have been developed. These designs have successfully achieved modulation bandwidths exceeding 45 GHz [16-21].

In this study, we propose a DFB+R laser specifically engineered to satisfy the demands of 6G data centers. By incorporating the detuned-loading effect and PPR effect and precisely controlled by facet reflectivity engineering, we achieve a stable operation and supports data rates exceeding 100 Gbps.

II. EXPERIMENTAL RESULTS

Figures 1(a) and 1(b) shows the schematic and scanning electron microscope (SEM) image of the fabricated a DFB + R laser. Our device is formed on compressively strained InAlGaAs multiple quantum wells (MQWs), a separate confinement heterostructure (SCH) layer, and an asymmetric grating layer for single mode lasing. The DFB section of our device has a length of 130 µm, while a 120 µm passive waveguide section is monolithically integrated using a butt-joint process.

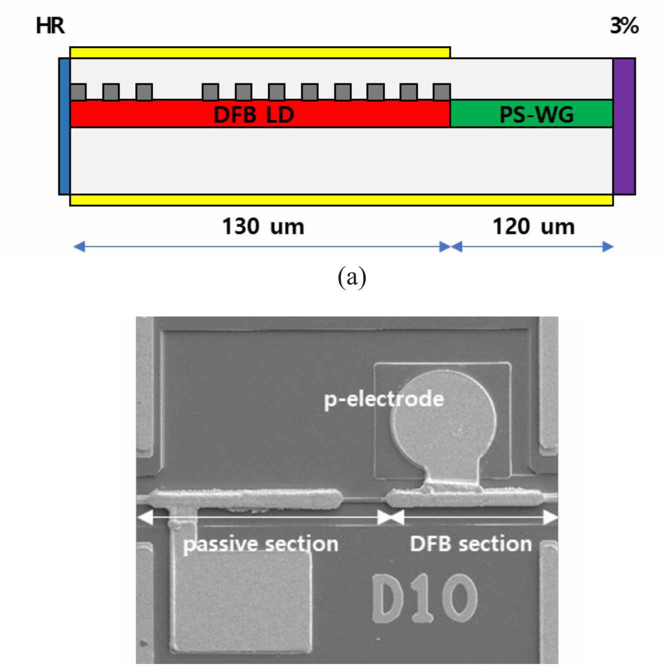

Fig. 1. (a) Schematic and (b) SEM image of the fabricated a DFB + R laser.

Unlike conventional DFB laser diodes, which typically apply high-reflection (HR) and anti-reflection (AR) coatings on the rear and front facets respectively, our device applies an HR coating on the rear facet (DFB side) and a low-reflectivity coating (~3%) on the front facet (passive waveguide side). A low-reflectivity front facet coating (~3%) is intentionally applied to effectively induce both the detuned-loading effect and photon–photon resonance (PPR).

Figure 2 shows the optical output characteristics of fabricated a DFB + R laser under different temperature conditions. The threshold currents at 25 °C is 5 mA, and the output power increases linearly up to approximately 56 mA, where a distinct kink is observed. This kink is attributed to the PPR effect, which is induced by the interaction between the main mode and a side mode. As a result of this phenomenon, our device can achieve higher modulation speeds compared to conventional DFB laser diodes.

Figure 3 shows the optical spectra of the fabricated DFB + R laser under various bias conditions. Our device exhibits a side mode suppression ratio (SMSR) exceeding 50 dB across the entire current range, and a PPR-induced side mode (f_{PPR}) is

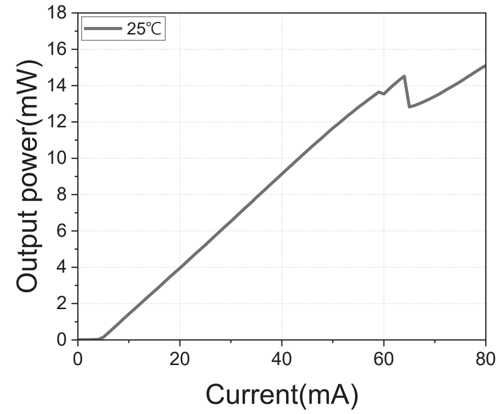

Fig. 2. Optical output powers of a DFB + R laser depending on the bias currents at 25 ℃.

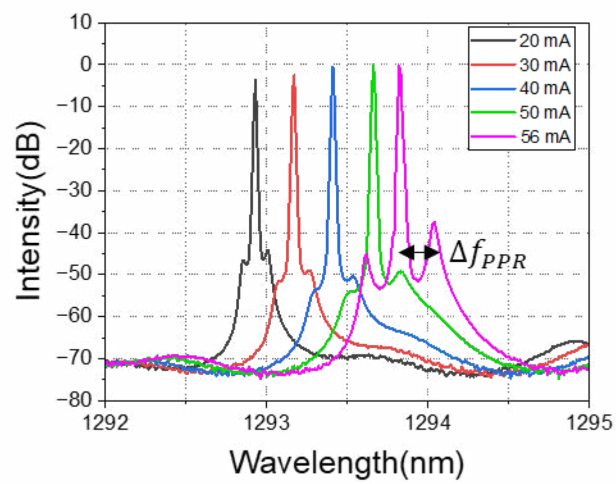

Fig. 3. The optical spectra of a DFB + R laser at various bias conditions.

observed at approximately 56 mA. The frequency spacing (Δf_{PPR}) between the main mode and f_{PPR} is approximately 36 GHz, which enables estimation of the corresponding 3-dB bandwidth.

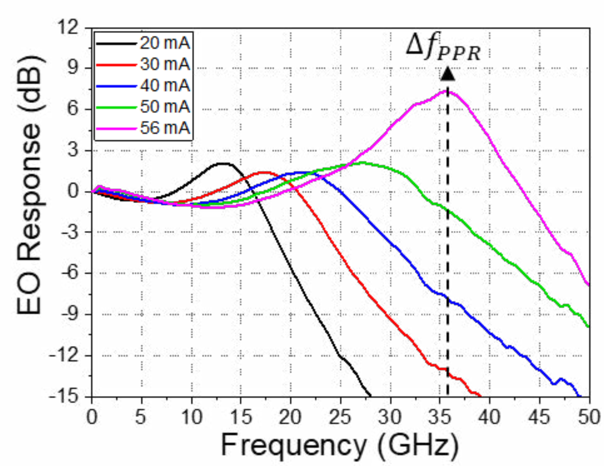

Fig. 4 Measured E/O response curves of DFB + R laser from 20 to 56 mA.

Figure 4 shows the electro-optical (E/O) response curves of a DFB + R laser chip die-bonded on a copper–tungsten (CuW) block with a flexible printed circuit board. The solid lines represent the measured E/O response at bias currents ranging from 20 to 56 mA. In the low-current region, our device exhibits characteristics dominated by its intrinsic relaxation oscillation frequency (f_r)) similar to conventional DMLs. As the bias current increases to the mid-current region, a noticeable enhancement in the 3-dB bandwidth is observed due to the detuned-loading effect. In the high-current region, additional bandwidth broadening occurs due to PPR, leading to a measured 3-dB bandwidth of approximately 46 GHz at 56 mA.

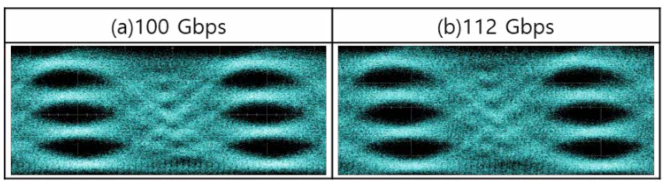

Fig. 5 Eye diagrams at (a)100 Gbps, (b) 112 Gbps PAM-4 modulations with I = 52 mA.

Figure 5 presents the back-to-back (BTB) eye diagrams for PAM-4 modulation at 100 Gbps and 112 Gbps, both measured with a bias current of 52 mA. As depicted in Fig. 4, a DFB + R laser exhibits a 3-dB bandwidth of approximately 46 GHz, significantly influenced by the PPR effect. Eye diagram measurements were conducted by precisely adjusting the bias current to operate within the peak bandwidth region. For quality assessment, a sampling oscilloscope was used to evaluate the extinction ratio (ER) and transmitter and dispersion eye closure quaternary (TDECQ). We obtained an outer ER of 3.549 dB and a TDECQ of 0.93 dB at 100 Gbps, and an ER of 3.553 dB and a TDECQ of 1.26 dB at 112 Gbps. These results clearly indicate that the proposed device is capable of supporting PAM-4 modulation signals exceeding 100 Gbps, demonstrating its strong potential for use in high-speed optical transmitters.

III. CONCLUSION

In this study, we have experimentally demonstrated the potential of DFB + R laser as an optical transmitter operating beyond 100 Gbps under PAM-4 modulation. Our devices employ a 3% reflectivity coating on the front facet to induce both the detuned-loading and PPR effects. We obtained a Δf_{PPR} of approximately 36 GHz at 56 mA, and E/O response measurements confirmed a 3-dB bandwidth of around 46 GHz. At data rates of 100 Gbps and 112 Gbps, the measured dynamic outer ERs were 3.549 dB and 3.553 dB, respectively, and the corresponding TDECQ values were 0.93 dB and 1.26 dB, respectively. These results validate the feasibility of the proposed device as a compact, high-speed optical source for next-generation data center applications.

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