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Original Paper

High-reliability, High-performance 25 Gb/s Directly Modulated Uncooled Lasers for 5G Wireless Communications

Jack Jia-Sheng Huang[1*], S.C. Huang[1], NiYeh Wu[1], Deo Yu[1], C.K. Wang[1], Ansel Chen[1], David Klotzkin[1], Yu-Heng Jan[1], ChunKo Chen[1], H.S. Chen[1] & Emin Chou[1]

[1] Source Photonics, No.46, Park Avenue 2nd Rd., Science Park, Hsinchu, Taiwan

[*] Jack Jia-Sheng Huang, E-mail: jshuang6@yahoo.com

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Abstract

Semiconductor laser diodes are important components for fifth-generation wireless technologies. To meet 5G wireless specifications, ever increasing performance and reliability requirements of each component become necessary to guarantee uptime air service. In this paper, we present highly reliable 25G DFB uncooled lasers that exhibit low threshold current, high single-mode, high bandwidth, and excellent eye pattern for uncooled operations of -40 to 85℃. Ultra-high component reliability is demonstrated to ensure stable operations for 5G mobile communications.

Keywords

Reliability, directly modulated lasers, DML, 25G DFB, 5G wireless, mobile network, safety, national security, cellular tower

1. Introduction

One of the key issues in the United States-China trade war involves technologies (Ellyatt, 2019; Reardon, 2019; Harrell, 2019). Among various technology segments, wireless communication is perhaps the area that draws most attentions and negotiations. The U.S. and China are locked in a race to dominate the next wave of wireless communications, namely fifth-generation, 5G (Lee, 2020; Soon, 2019; Tcheyan & Bresnick, 2020). The 5G wireless networks promise to empower mobile phones, self-driving vehicles, artificial intelligence (AI), internet of things (IoT), military, and space applications (Huang, Jan, Yu, Chang, Chang, Shiu, Ren, Wang, & Chou, 2018; Nordrum, 2017; https://en.wikipedia.org/wiki/5G).

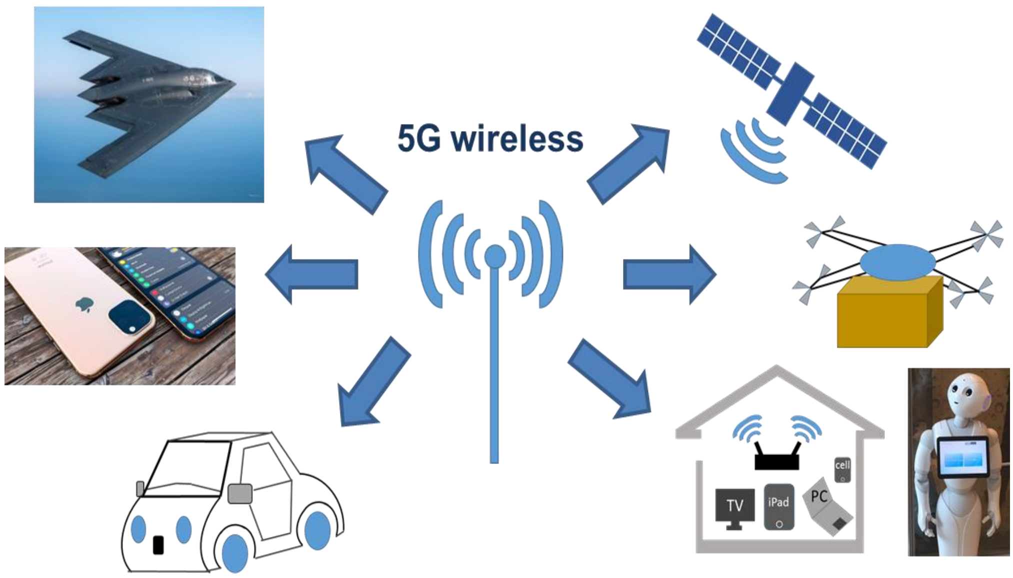


Figure 1. 5G Wireless Applications Including 5G Mobile Phones, Autonomous Vehicles, IoT, Robots, Drones, Satellites, Aerospace, etc.

Unlike 4G and other previous generations, 5G wireless is the network that communicates with all elements. The 5G mobile network requires ultra-high reliability to guarantee uptime air service for several reasons (shown in Table 1). The first is principally for safety (Nelson, 2017; Cohen, 2019). For example, one cannot have a self-driving car that doesn't transmit data properly. Physicians, especially in remote areas, need to access healthcare data timely and accurately to provide the best possible medical treatments to their patients. The second regards national security (Hoehn & Sayler, 2020; Vincent, 2020; Barnett, 2020; Overview of risks introduced by 5G adoption in the United States, 2019). At the present, U.S. forces extensively use mid-band (1-6 GHz) and low band (<1 GHz) frequencies. Careful evaluation and caution need to be exercised before finalizing the plan to sharing some of the spectrum with commercial usage. The other national security concerns include the use of foreign equipment in the deployment of 5G wide-area network, cyberattacks, and perpetration. The third is concerning repairment cost and tower climber's well-being (Keith, 2019; Rambo, 2019). For example, fronthaul wireless network involves connection between cellular towers, macro cells, metro cells, and base stations. High reliability at the component level for each wireless tower is required to guarantee uptime performance, avoid time consuming repair, and minimize tower climbing. The failure rate requirement for 5G mobile is typically <0.1% versus 1-2% for CATV or telecommunication applications.

Table 1. Reasons for Ultra-high Reliability for 5G Wireless Applications

Aspects of high reliability	5G applications	Reasons for high reliability
Safety	- Self-driving car	- Autonomous cars need to transmit data properly all time to maintain safe street driving
	- Healthcare	- Physicians need to access patients' data timely and accurately
National security	- Military	- Command and control (C2) need 5G signals to reduce latency from satellites
	- Space	- Spacecraft needs highly accurate data for launch, space travel, and landing
Repair	- Fronthaul wireless	- Wireless cellular towers need high reliability to minimize repair cost and tower climbing

Reliability is ultimately the principal denominator to determine the success of the 5G wireless components. Due to the high reliability requirement in 5G, component suppliers need to guarantee the chip reliability to the ever increasingly stringent level. One of the most challenging reliability issues is to assure continuous uptime operation for source lasers. This is because the laser diode needs to meet both high-speed (25 Gb/s) and high reliability where engineering tradeoff may occur. For example, high-speed laser typically requires a design of short cavity that would lead to high current density and accelerated degradation rate.

In this paper, we have demonstrated highly reliable 25 Gb/s directly modulated lasers for 5G mobile applications. We show low drive current, high modulation bandwidth, and clear eye opening for the modulation of 25 Gb/s. Long-term reliability is established to meet the ultra-high reliability requirement for 5G.

2. Experimental

First, the n-type indium phosphide (InP) epitaxial layer was grown on S-doped n-type InP substrate as the buffer using metal organic chemical vapor deposition (MOCVD). The active region of InGaAlAs multi-quantum well (MQW) was grown to achieve high optical confinement for ridge waveguide (RWG) structure, as shown in Figure 2(a). The grating layer of InGaAsP was then grown and patterned by holographic technique to form distributed feedback (DFB) laser (Huang & Jan, 2017). To improve the single-mode DFB performance, non-uniform grating involving mixed pitch was employed as illustrated in Figure 2(b). The p-InP cladding was overgrown directly on top of the grating layer. Finally, the contact layer was formed with the heavily-doped p^+-InGaAs to make Ohmic contact with Ti/Pt/Au p-metal.

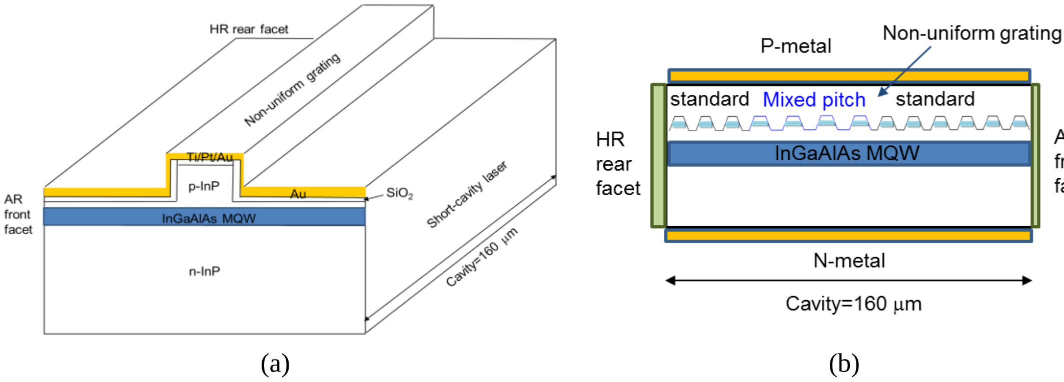


Figure 2. (a) Schematics of 25 Gb/s DFB Laser Showing the Ridge Waveguide Structure and (b) Cross-Sectional View of the Laser Structure

For 25 Gb/s DFB laser, the wafer was cleaved into 160 m bars and coated with anti-reflection (AR) and high-reflection (HR) films. The mirror coating reflectivities of AR and HR were around <1% and 80%, respectively. The laser chip was mounted on transistor outline (TO) header. Gold wire was bonded to connect the p-metal contact of the laser chip to the lead of the TO header. Finally, the laser TO was assembled to high-speed optical module for 25 Gb/s modulation eye diagram test.

The burn-in and reliability tests were conducted on TO samples. The laser was screened by burn-in based on the condition of 110°C, 85 mA for 24 hours. The long-term reliability aging was tested at 90°C with a constant stress current of 65 mA. The failure criterion for aging test was defined as 50% increase in the initial threshold current.

3. Results and Discussions

Figure 3 shows the light versus current (LI) curves at various temperatures. The 25 Gb/s DFB laser showed very low threshold current (I_{th}) of 9.5 mA at 25°C. The threshold current remained low at high temperatures, about 15.0 and 18.0 mA at 70 and 85°C, respectively. At low temperature, the I_{th} was about 7.5 mA at -40°C.

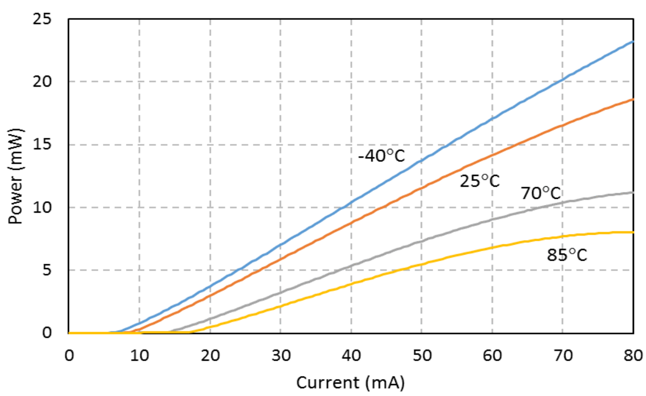


Figure 3. LI Curves of the 25 Gb/s DFB Laser Showing Over-temperature Characteristics in the Range of -40 to 85°C

Figure 4 shows the optical spectra of the 25 Gb/s DFB laser measured at -40, 25 and 85°C. The laser showed excellent single-mode performance with side-mode-suppression-ratio (SMSR) of about 45 dB. The high SMSR was attributed to the non-uniform grating associated with the mixed-pitch design.

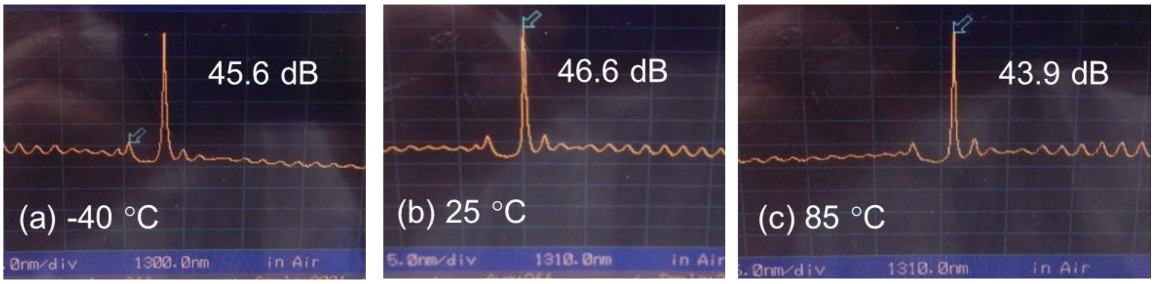
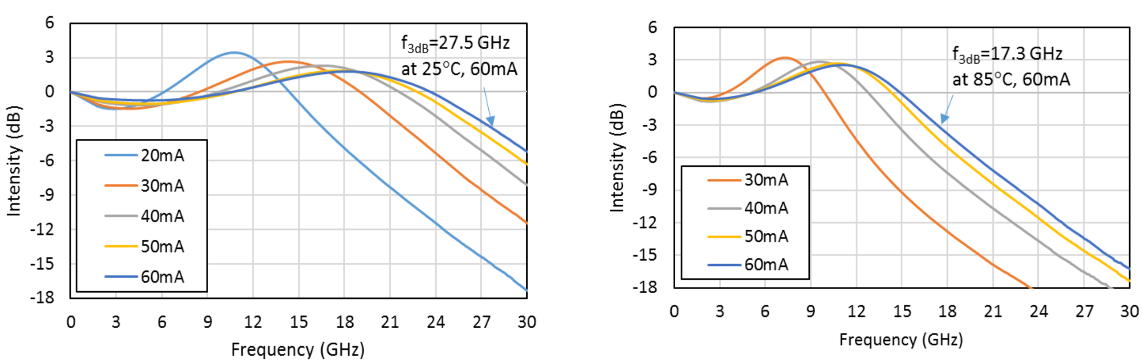


Figure 4. Optical Spectra of the 25 Gb/s DFB Laser Showing Single-mode Bragg Wavelength (a) -40°C, (b) 25°C and (c) 85°C

Figure 5 shows the small-signal modulation bandwidth of the 25 Gb/s DFB laser measured at various bias current ranging from 20 to 60 mA. At the bias current of 60 mA, the 3dB bandwidth reached 27.5 and 17.3 GHz at 25 and 85°C, respectively. Figure 6 shows the relaxation oscillation frequency (f_r) against the square root of modulation current at 25 and 85°C. High resonance frequency slopes for uncooled operations have been achieved. The slopes of f_r were estimated to be 3.0 and 1.9 GHz/mA$^{1/2}$ for 25 and 85°C, respectively. The values of the slopes were comparable to those reported in the InGaAlAs buried heterostructure (Takada, Matsuda, Okumura, Ekawa, & Yamamoto, 2006) and ridge waveguide lasers (Paoletti et al., 2009; Nakahar, Wakayama, Kitatani, Fukamachi, Sakuma, & Tanaka, 2014).



(a) (b)

Figure 5. Small Signal Modulation Bandwidth of the 25 Gb/s DFB Laser at Various Bias Current in the Range of 20-60 mA at (a) 25°C and (b) 85°C

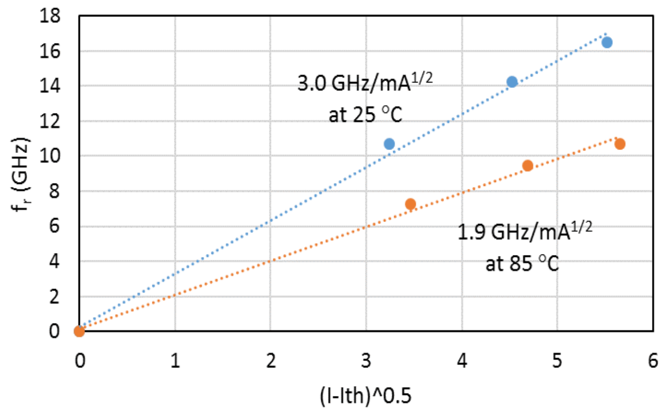


Figure 6. Relaxation Oscillation Frequency Versus Bias Current of the 25 Gb/s DFB Laser at 25 and 85°C. Interpolated Slopes Show 3.0 and 1.9 GHz/mA$^{1/2}$ for 25 and 85°C, Respectively

Figure 7(a)-(c) shows the eye diagrams of 25 Gb/s modulation measured at -40, 25 and 85°C. The bias current and modulation current were set at 35.2 and 22.4 mA, respectively. Figure 8 shows the eye mask margin over the wide temperature range of -40 to 85°C. The 25 Gb/s DFB laser achieved high mask margin (>35%) for the extinction ratio of 4.5 dB, substantially higher than the eye-opening requirement of 15%.

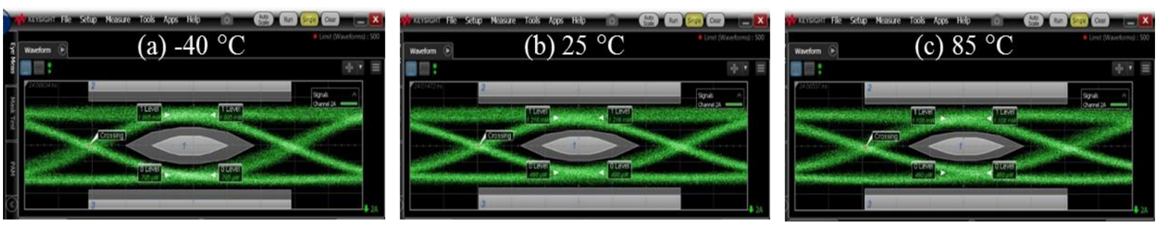


Figure 7. Eye Diagram at 25Gb/s at -40, 25 and 85°C

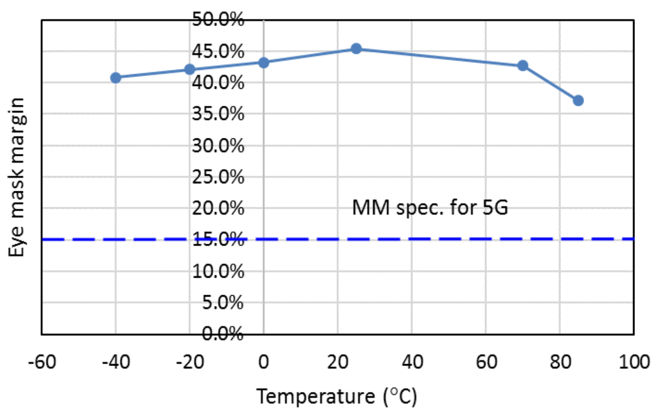


Figure 8. Eye Mask Margin at 25 Gb/s at -40, 25 and 85°C. The Lasers Show Excellent Mask Margin for Uncooled Operations from -40 to 85°C

Figure 9 shows the aging plot of the 25G DFB laser that was subjected to the stress condition of 90°C, 65 mA. The relative change of threshold current was monitored during aging test, and no failure occurred after 3300 hours. Based on the small change in threshold current, robust long-term reliability of the 25G DFB lasers has been demonstrated to meet 5G wireless requirement. We attribute the high reliability to the optimized design in the quantum well and optical coating. With the optimization of design and process, the common issues of InGaAlAs lasers such as sudden failure or catastrophic optical damage (COD) have been successfully eliminated (Jiménez, 2003; Hempel et al., 2013; Fukuda, Okayasu, Temmyo, & Nakand, 1994; Tomm, Ziegler, & Elsaesser,, 2011; Huang, 2014, 2005; Hausler, Zeimer, Sumpf, Erbert, & Trankle, 2008; Chuang, Nakayama, Ishibashi, Taniguchi, & Nakano, 1998; Huang, Nguyen, Hsin, Aeby, Ceballo, & Krogen, 2005; Ott, 1997).

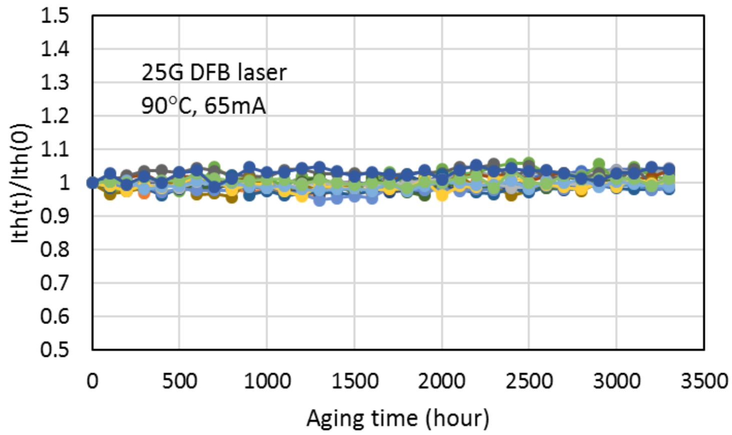


Figure 9. Aging Plot of 25 Gb/s DFB Laser Based on the Stress Condition of 90°C, 65 mA

4. Conclusion

We have demonstrated stable single-mode performance of 25 Gb/s DML for uncooled operations (-40 to 85°C). The 25 Gb/s DFB lasers show low drive current and excellent single-mode performance. The lasers also show high bandwidth with 3dB readpoint of 17.3 GHz at 85°C, 60 mA. At 25 Gb/s modulation, the eye opening was excellent for uncooled conditions (-40 to 85°C), with good mask margin (>35%) over the 15% requirement.

With optimized design in the quantum well and optical coating, we also achieve robust reliability performance with the aging data over 3300 hours.

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