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High-Power High-Modulation-Speed 1060-nm DBR Lasers for Green-Light Emission

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***Abstract*—We report on the static and dynamic performance of high-power and high-modulation-speed 1060-nm distributed Bragg reflector (DBR) lasers for green-light emission by second-harmonic generation. Single-wavelength power of 387 mW at 1060-nm wavelength and green power as high as 99.5 mW were achieved. A thermally induced wavelength tuning of 2.4 nm and a carrier-induced wavelength tuning of −0.85 nm were obtained by injecting current into the DBR section. Measured rise–fall times of 0.2 ns for direct intensity modulation and 0.6 ns for wavelength modulation make the lasers suitable for >50-MHz green-light modulation applications.**

***Index Terms*—Distributed Bragg reflector (DBR) laser, frequency conversion, green-light generation, laser projection display, nonlinear optics, optical waveguides, second-harmonic generation (SHG), semiconductor laser, wavelength tuning.**

I. INTRODUCTION

GREEN laser emission is of great interest for many applications including medical surgery and sensing. Recently, projection displays based on red, green, and blue (RGB) lasers and scanning mirrors attracted much attention as these RGB laser displays offer high-contrast and color-rich images even on curved surfaces and can potentially be made as compact as a cell phone. The requirements for lasers as light sources for RGB laser displays are high power, low noise, high modulation speed, and small footprint. Semiconductor blue lasers based on a GaN material system [1] and semiconductor red lasers based on a GaAs [2] material system have become commercial products and are likely to meet these requirements. However, high-power semiconductor green lasers have yet to be demonstrated. On the other hand, second-harmonic-generation (SHG) effect of a nonlinear crystal was commonly used to generate green emission by the 1064-nm wavelength of a diode-pumped solid-state (DPSS) laser with an intracavity configuration [3]. But a DPSS green laser cannot be directly modulated at high speed due to the long fluorescent lifetime of the solid-state gain material and the intracavity configuration. Therefore, the lacking of high-power, high-speed, and compact green lasers remains one of the most challenging difficulties for the RGB laser display application.

In this letter, we report the static and dynamic performance of semiconductor 1060-nm distributed Bragg reflector (DBR) lasers for green-light emission. The combination of a semiconductor DBR laser and an SHG waveguide with a single-pass configuration [4] offers various advantages such as high power, low noise, high modulation bandwidth, wavelength tunability, high efficiency, compactness, and potential low cost of manufacturing and integration. In contrast to the high-power distributed feedback lasers that we reported previously for green-light generation [5], the DBR lasers' wavelength can be tuned by thermal effect or by carrier effect to match to the SHG center wavelength.

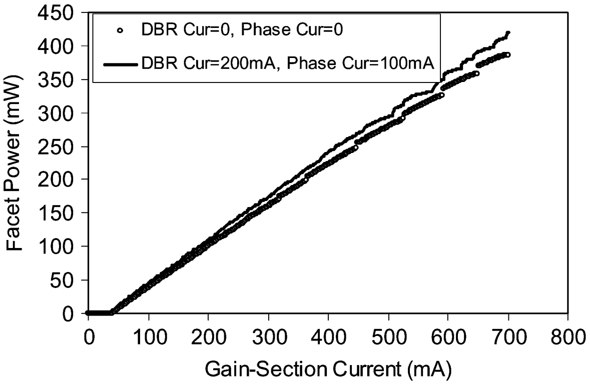

Fig. 1. Facet power of a DBR laser versus gain-section current for DBR current $= 0$, phase current $= 0$; and DBR current $= 200$ mA, phase current $= 100$ mA.

II. 1060-nm DBR LASER FABRICATION

The 1060-nm DBR lasers are designed with three sections. A high-efficiency gain section combines with wider bandgap phase and DBR sections used for wavelength tuning. The vertical structure is based on an optimized high-power 1060-nm Fabry–Pérot laser [6] with a GaInAs strained quantum-well sandwiched by AlGaAs layers to form a graded-index-separate-confinement heterostructure.

The structure is grown using low-pressure organometallic vapor phase epitaxy. A quantum-well impurity-free intermixing technique is used to selectively increase the bandgap at the phase and DBR sections relative to that at the gain section to minimize the optical absorption in the these two passive sections [7]. In the upper cladding layer of the DBR section, an aluminum-free grating layer is inserted. Lateral light confinement is provided by a raised-ridge waveguide.

III. PERFORMANCE OF 1060-nm DBR LASERS

Submounted DBR lasers are placed by contact probes on temperature-controlled plate for characterization. Fig. 1 shows light–current curves of the gain section of a typical DBR laser at 25 °C with and without current injections to the DBR and

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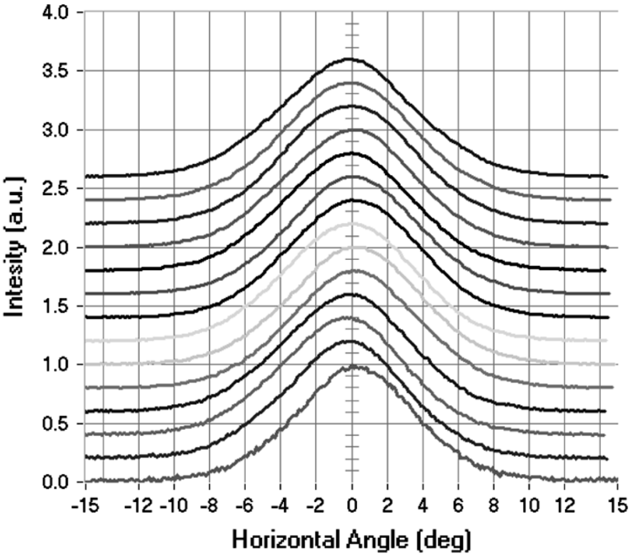

Fig. 2. Horizontal far-field patterns at various gain-section current from 50 to 700 mA in steps of 50 mA.

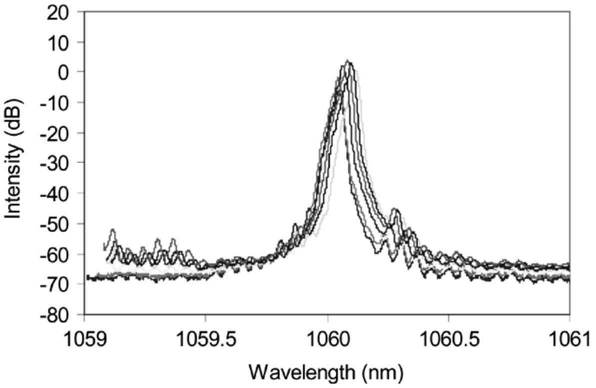

Fig. 3. Optical spectrum at various gain-section currents from 100 to 700 mA in step of 100 mA.

phase sections. With current injections to DBR and phase sections, the maximum optical power at gain current of 700 mA increases from 387 to 419 mW and the threshold current decreases from 40 to 34 mA, mostly due to the optical crosstalk instead of the electrical crosstalk between the gain section and the DBR and phase sections. When currents are injected into the DBR and phase sections, amplified spontaneous emission with energy larger than the gain-section bandgap is created and is absorbed at the gain section. Thus, extra carrier density at the gain section is generated. The electrical isolation resistance between the gain and phase sections is measured to be 1.5 KΩ and the electrical isolation resistance between the DBR and gain sections is measured to be 3 KΩ.

Fig. 2 plots the horizontal far-field patterns at various gain-section current at 25 °C without current injections to the DBR and phase sections. Although the far-field patterns have slight beam steering, they remain single-lobed and nearly symmetric up to 700 mA. Fig. 3 shows the optical spectra of the DBR laser at various gain-section currents at 25 °C. Single-wavelength power of 387 mW corresponding to gain-section current of 700 mA is obtained. The sidemode suppression ratio is >46 dB and the wavelength variation is <0.12 nm over the whole current range from 100 to 700 mA. We believe even higher power is possible if the gain-section drive current is beyond 700 mA.

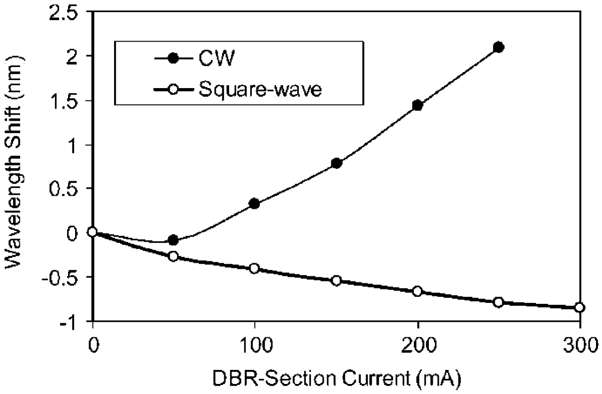

Fig. 4. Wavelength tuning by the carrier effect only and by combination of the carrier and thermal effects.

To study the wavelength tuning with DBR-section current, we first measured the wavelength shift when continuous-wave (CW) current was applied to the DBR section. There is a 0.3-nm blue shift when the DBR-section current is 50 mA and then the wavelength shift becomes red shift because the thermal effect overwhelms the carrier effect as the DBR current continues to increase. A total red shift of 2.1 nm is obtained at DBR current of 250 mA, as shown in Fig. 4.

In order to measure the carrier-induced wavelength shift without thermal effect, we modulated the DBR current with a 5-MHz and 50% duty-cycle square wave and measured the separation of the two tones of the DBR laser wavelength. A carrier-induced wavelength shift of −0.85 nm is obtained at DBR current amplitude of 300 mA (Fig. 4).

The thermally induced wavelength shift can be used to statically match the laser wavelength and the SHG center wavelength for efficient green-light generation in order to compensate for manufacturing tolerance or environmental temperature change, while the carrier-induced wavelength shift can be used to modulate the green-light intensity at high speed, as discussed in Section IV.

The direct intensity modulation waveform of the DBR laser is obtained by modulating the gain-section current via a high-speed microprobe with 48-Ω impedance matching resistor. The low level of the modulation current is slightly above the threshold current and the modulation depth is 40 mA, which is limited by the power rating of the microprobe. A rise–fall time of 0.2 ns was observed, in agreement with the measured small-signal 3-dB bandwidth of 2 GHz.

IV. GREEN-LIGHT GENERATION AND MODULATION

A high CW green-light power of 99.5 mW was demonstrated by coupling the infrared (IR) output of a DBR laser similar to that of Fig. 4 into an SHG waveguide made of a periodically poled MgO-doped lithium niobate (PPLN) crystal. The experimental setup is similar to that in [5]. The green-light power at the SHG waveguide output facet versus IR power that is coupled into the SHG waveguide is plotted in Fig. 5. The IR-to-

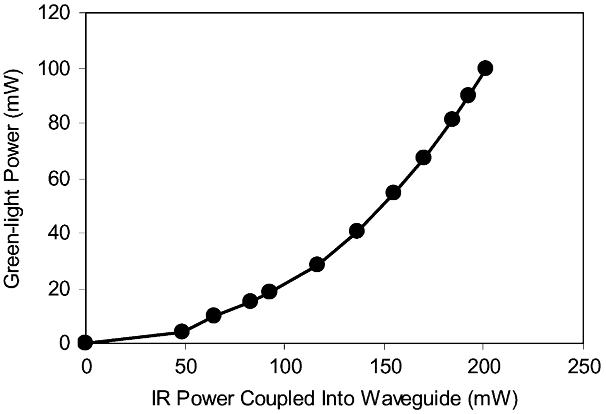

Fig. 5. Green-light power as a function of IR power coupled into the SHG.

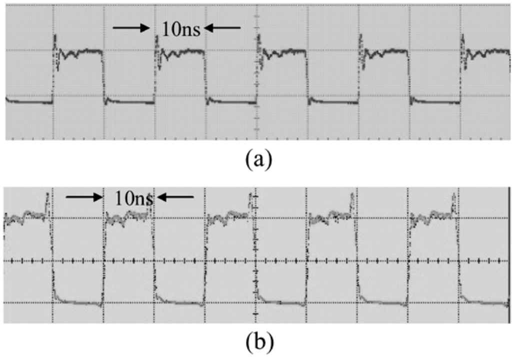

Fig. 6. Green-light intensity waveform at 50 MHz of a green-light module under (a) direct intensity modulation with gain-section current and (b) wavelength modulation with DBR-section current.

green conversion efficiency is 49.4% at the maximum green-light power.

The modulation characteristics were measured for a packaged compact green-light module. A green-light module contains one DBR laser, one PPLN SHG waveguide, and two microlenses for coupling. Heating elements are also incorporated in the package for wavelength matching between the laser and the SHG waveguide in addition to the wavelength tuning with the DBR and phase sections. Fig. 6(a) shows the green-light intensity waveform when the gain section is injected with a 50-MHz 50% duty-cycle square-wave current that swings between 50 and 250 mA, and Fig. 6(b) shows the green-light intensity waveform when the DBR section is injected with a 50-MHz 50% duty-cycle square-wave current that swings between 10 and 210 mA. For DBR section modulation, the intensity modulation of the green light is created by the wavelength changing of the IR light with respect to the PPLN center wavelength. Although the optical waveforms have overshoots caused by electrical parasitics of the evaluation board where the green-light module is mounted, they clearly demonstrate that the green-light module is capable of being modulated at frequency higher than 50 MHz. A rise–fall time of 0.5 ns was measured for the case of gain-section current modulation and a rise–fall time of 0.6 ns was measured for the case of DBR-section current modulation.

Generally, modulating the currents into a DBR laser according to the random color content of a video image also changes the temperature of the laser, leading to an undesirable patterning effect. The lasing wavelength depends not only on the instantaneous currents but also the history of the heat load and the heat dissipation. The thermal patterning effect and solutions to it will be discussed elsewhere.

V. CONCLUSION

We have demonstrated a high output power of 387 mW from a 1060-nm DBR laser and green-light power as high as 99.5 mW by frequency-doubling with a PPLN crystal. Moreover, we have demonstrated that a 1060-nm DBR laser can be direct intensity modulated or wavelength modulated to produce desirable green-light modulation at frequency of 50 MHz.

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