

# High-Power Continuous-Wave Single-Longitudinal-Mode Operation of an Optically Pumped DFB Laser at $\lambda \sim 3.64 \mu\text{m}$

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**Abstract**—High-power continuous-wave (CW) single-longitudinal-mode emission at  $3.64 \mu\text{m}$  is obtained from an optically pumped distributed-feedback (DFB) laser. The Bragg stopband and two degenerate DFB modes are observed at certain pump powers. The laser incorporates 14 InAs–InGaSb–InAs type-II quantum wells imbedded in an InGaAsSb waveguide. The index-coupled 1-D grating is fabricated in the top clad using interference lithography and plasma etching. A  $110\text{-}\mu\text{m}$ -wide stripe from a  $1.9\text{-}\mu\text{m}$  CW laser provides both optical pumping and gain guiding. Record high output power of more than 560 mW per side is obtained at 80 K. The wavelength is tunable over a 6.8-nm range by varying the pump power from 1 to 8.1 W.

**Index Terms**—Distributed-feedback (DFB) lasers, optical pumping, quantum-well lasers, semiconductor lasers.

## I. INTRODUCTION

THE 3- to  $5\text{-}\mu\text{m}$  midinfrared (midIR) atmospheric transmission window contains many fundamental molecular vibration lines, including the important C–H stretch region at  $\sim 3.3 \mu\text{m}$ . Spectroscopic applications within this wavelength range require a laser source with high output power, good beam quality, and extensive wavelength coverage. The most promising technologies include single-stage type-II W lasers [1], interband cascade (IC) lasers [2], and intersubband quantum cascade (QC) lasers [3]. For spectroscopic applications, narrow linewidth and wavelength tunability are desired and can be achieved by incorporating distributed-feedback (DFB) grating in the laser. Continuous-wave (CW) or quasi-CW operation is also important because chirp effects broaden the laser linewidth in pulsed mode.

Recently, significant improvements have been made to IC- and QC-DFB lasers. Meyer *et al.* achieved an output power of 41 mW from  $3.44\text{-}\mu\text{m}$  CW single-mode IC-DFB lasers working at 120 K [4]; Yang *et al.* achieved CW operation up to 261 K on single-mode IC-DFB lasers near  $3.3 \mu\text{m}$  [5]; Yu *et al.* reported output power of 135 mW from  $4.8\text{-}\mu\text{m}$  CW single-mode QC-DFB lasers working at 298 K [6]. Meanwhile, significant

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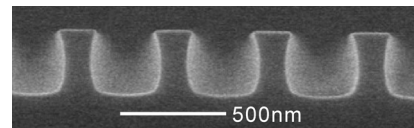


Fig. 1. Cross-sectional scanning electron microscope picture of the DFB grating.

improvements have been made by Kaspi *et al.* on optically pumped noncascaded type-II W lasers. A low-confinement integrated-absorber design enabled very high output power of 11 W in a quasi-CW operation at 84 K [7], [8]. The high output power, high brightness, suppressed filamentation, and large wavelength coverage from 2.4 to  $9.3 \mu\text{m}$  make these lasers attractive for spectroscopic applications in the midIR region. We fabricated a DFB grating in one of these lasers and achieved high output power at  $\lambda = 3.64 \mu\text{m}$  and large wavelength tunability [9]. Improved alignment and sample cooling have resulted in strongly improved performance; more detailed spectral information such as Bragg stopband and side lateral modes have been obtained through higher resolution spectral measurements. In this letter, new record high output power of 560 mW per side is reported in a CW single-longitudinal-mode (SLM) operation at 80 K. A linewidth of  $\geq 0.17 \text{ nm}$  and DFB stopband of 1.6 nm are clearly observed. Wavelength tunability of 6.8 nm is also demonstrated. Linewidth broadening and DFB mode degeneracy at certain pump conditions are discussed in comparison with other work.

## II. FABRICATION

The laser device was epitaxially grown by molecular beam epitaxy [8]. It consists of a GaSb:Te substrate, a  $4\text{-}\mu\text{m}$ -thick GaSb bottom clad layer, a  $1.5\text{-}\mu\text{m}$ -thick active region consisting of 14 type-II InAs–InGaSb–InAs W quantum wells, and a  $1.25\text{-}\mu\text{m}$ -thick top clad layer in which the 1-D Bragg grating was fabricated using interference lithography and inductive coupled plasma etching (see Fig. 1). The measured grating period is 488.2 nm with a duty cycle of 33%, and the grating depth is 350 nm. The index coupling strength is estimated to be  $\kappa \sim 4 \text{ cm}^{-1}$ .

The wafer was then lapped and polished to a thickness of about  $150 \mu\text{m}$  and cleaved into 2.5-mm-long cavity, which gives a nominal grating-coupling product of  $\kappa L \sim 1$ . The grating was tilted  $6^\circ$  from the facet to suppress the facet Fabry–Pérot (F-P) modes, when the optical pump stripe is perpendicular to the grating (see Fig. 2(d) inset). The laser is, therefore, analogous to

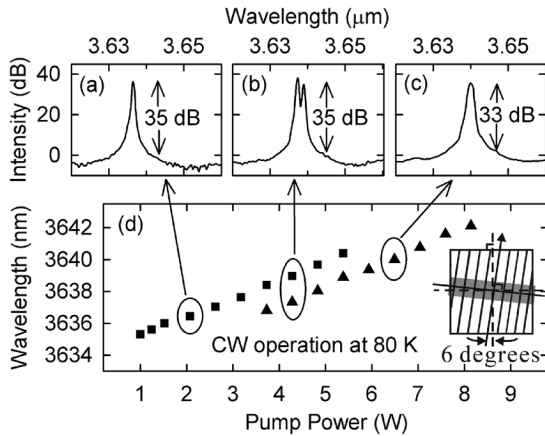


Fig. 2. (a)-(c) DFB spectra under pump power of 2, 4.2, and 6.5 W, respectively. (d) Lasing wavelength of the DFB laser working at 80 K.

a traditional DFB with antireflection coating on both facets, and should not be confused with  $\alpha$ -DFB laser [10], for which the pump stripe is parallel to the tilted grating. The sample was indium soldered (epi-side up) to a copper heat sink and mounted in a liquid nitrogen cooled cold-finger dewar. The collimated beam of the 1908-nm CW fiber laser was focused by a cylindrical lens into a stripe at the surface of the DFB laser to provide pumping and gain guiding in the lateral direction. Maximal power conversion efficiency was obtained when the pump stripe was 110  $\mu\text{m}$  wide (full-width at half-maximum).

### III. RESULTS

The device lases when the pump power exceeds the 1-W threshold. The output beam was collimated and passed through a 2.5- $\mu\text{m}$  long-pass-filter to remove any residual pump light, and then focused onto the 10- $\mu\text{m}$ -wide entrance slit of a 1/2-m monochromator with spectral resolution of 0.2 nm. A 77 K InSb photodiode was used to detect the light with standard signal processing electronics. Fig. 2 shows the wavelength and spectra of the DFB laser under CW operation at 80 K. When the pump power is less than 3.5 W, CW SLM operation is obtained on the longer wavelength side of the stopband. The sidemode suppression ratio (SMSR) is more than 35 dB [see Fig. 2(a)]. When the pump power is between 3.5 and 5.5 W, degenerate DFB modes on both sides of the stopband lase simultaneously [see Fig. 2(b)]. The separation of 1.6 nm corresponds to the coupling coefficient  $\kappa = 3.8 \text{ cm}^{-1}$ , in good agreement with the original estimate of  $\sim 4 \text{ cm}^{-1}$ , and also the fact that the device is purely index-coupled with little reflection from the facet. Similar mode degeneracy has also been reported by Yang *et al.* in index-coupled midIR type-II IC-DFB lasers [11]. Solutions such as adding gain/loss coupling and asymmetric facet coating are being investigated. As the pump power is increased to more than 5.5 W, CW SLM operation with SMSR more than 33 dB is again obtained, this time on the shorter wavelength side of the stopband [see Fig. 2(c)], and with a broadened linewidth. Detailed discussion of the linewidth is presented below. Fig. 2 also shows the wavelength tuning range of 6.8 nm due to thermal effects induced by varying the pump power from 1 to 8.1 W.

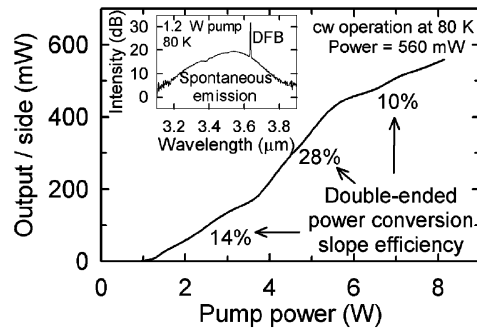


Fig. 3. Single-ended output power versus pump power of the DFB laser. Inset is the spontaneous emission spectrum collected from the top of the device.

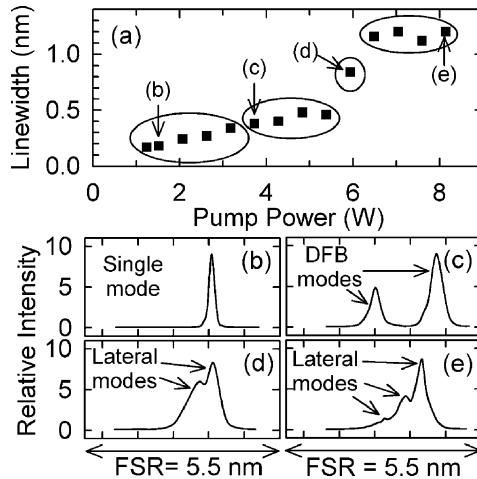


Fig. 4. (a) Linewidth of the DFB laser for CW operation at 80 K. (b)-(e) Laser spectra measured with F-P interferometer.

Under the same test conditions, a calibrated thermopile power meter was used to perform a power measurement. The output power as a function of the pump power is shown in Fig. 3. Three regions of operation with different power conversion slope efficiencies can be identified, related to the three spectral regimes. When the pump power is less than 3.5 W, the double-ended power conversion slope efficiency is 14%. It increases to 28% when the pump power is between 3.5 and 5.5 W and drops to 10% when the pump power is more than 5.5 W. The correlation between the different modes of operation and power conversion slope efficiencies is still under investigation. The most important result of this experiment is the maximum power of 560 mW per side in a CW SLM operation. To the best of our knowledge, it is the highest reported output power from a midIR DFB laser under CW SLM operation. The inset of Fig. 3 shows the spontaneous emission spectrum from the top of the device working at the pump power of 1.2 W (1.2 times threshold). The DFB laser emission is 90 nm longer than the peak of the spontaneous emission spectrum. More power is likely to be produced from the device if the Bragg wavelength were adjusted to match the peak of the gain.

Whereas the monochromator has the resolution to distinguish different longitudinal modes, it cannot resolve the fine mode structure. We conducted another spectral measurement using the high-resolution F-P interferometer with free-spectral range of 5.5 nm. Fig. 4(a) shows the accurate laser linewidth at different

pump powers. As is in Figs. 2 and 3, three regions of operation can be identified. When the pump power is less than 3.5 W, the operation is strictly single-mode and the linewidth increases from 0.17 nm at threshold to 0.34 nm at 3.5 times threshold [see Fig. 4(b), cf. Fig. 2(a)]. When the pump power is between 3.5 and 5.5 W, lasing occurs on both side of the Bragg stopband and each side is still single-mode with a linewidth ranging from 0.34- to 0.46-nm [see Fig. 4(c), cf. Fig. 2(b)]. When the pump power is more than 5.5 W, the output is only on the short wavelength side of the stopband and the apparent linewidth increases to 1.2 nm [cf. Fig. 2(c)], due to higher order modes on the short wavelength side of the main DFB mode [see Fig. 4(d), (e)]. The mode spacing between these side modes is about 0.5 nm. They are identified as additional lateral modes, since the spacing between the longitudinal modes is 0.7 nm for the 2.5-mm cavity. The operation in this region is, therefore, classified as SLM with multiple lateral modes. Multilateral-mode operation in midIR type-II DFB has been reported previously [12]. They attributed the cause of the additional lateral mode to the relatively wide pump stripe. The same explanation can be given to our laser as the pump stripe is 110  $\mu\text{m}$  wide, seven times wider than the previous work. Lateral spatial hole burning and filamentation due to the linewidth enhancement factor (LEF) are common problems for broad-area gain-guided lasers [13]. They become more severe with wider pump stripe and higher pump power. Different LEF values from 0.7 to 5 have been reported for type-II W lasers [1], [10], [14], [15]. Although the low-optical-confinement design leads to significantly reduced filamentation in our laser, more than one lateral filament has been reported under F-P operation [7], [8]. The general trend of linewidth broadening is also due to these lateral inhomogeneities, because the refractive index and corresponding Bragg wavelength at different lateral positions become more divergent at higher pump powers.

#### IV. CONCLUSION

In summary, a record single-longitudinal, multilateral-mode output power of 560 mW per facet is demonstrated at 80 K from a 3.64- $\mu\text{m}$  CW DFB laser. The device is tunable over a range of 6.8 nm by varying the pump power. A relatively narrow linewidth of 0.17 nm is obtained near threshold. However, dual-DFB-longitudinal-mode operation at certain pump conditions and linewidth broadening due to multilateral-mode operation are observed. The causes of these effects are discussed and compared with the results from other groups. Improvements such as

gain/loss coupling and asymmetric facet coating are under development. This simple-designed CW optically pumped type-II DFB laser offers a promising high-power alternative to the popular IC-DFB and QC-DFB as a light source for the spectroscopic applications in the 3- to 5- $\mu\text{m}$  wavelength range.

#### REFERENCES

- [1] J. R. Meyer, C. A. Hoffman, F. J. Bartoli, and L. R. Ram-Mohan, "Type-II quantum-well lasers for the midwavelength infrared," *Appl. Phys. Lett.*, vol. 67, pp. 757–759, 1995.
- [2] R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells," *Superlattices Microstruct.*, vol. 17, pp. 77–83, 1995.
- [3] J. Faist *et al.*, "Quantum cascade laser," *Science*, vol. 264, pp. 553–556, 1994.
- [4] C. S. Kim, M. Kim, W. W. Bewley, C. L. Canedy, J. R. Lindle, I. Vurgaftman, and J. R. Meyer, "High-power single-mode distributed-feedback interband cascade lasers for the midwave-infrared," *IEEE Photon. Technol. Lett.*, vol. 6, no. 3, pp. 158–160, Feb. 1, 2007.
- [5] R. Q. Yang, C. J. Hill, K. Mansour, Y. Qiu, A. Soibel, R. E. Muller, and P. M. Echternach, "Distributed feedback mid-IR interband cascade lasers at thermoelectric cooler temperatures," *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 5, pt. 1, pp. 1074–1078, Sep/Oct. 2007.
- [6] J. S. Yu *et al.*, "High-power, room-temperature, and continuous-wave operation of distributed-feedback quantum-cascade lasers at  $\lambda \sim 4.8 \mu\text{m}$ ," *Appl. Phys. Lett.*, vol. 87, p. 041104, 2005.
- [7] R. Kaspi *et al.*, "High power and high brightness from an optically pumped InAs/InGaSb type-II midinfrared laser with low confinement," *Appl. Phys. Lett.*, vol. 81, pp. 406–408, 2002.
- [8] R. Kaspi *et al.*, "High performance optically pumped antimonide lasers operating in the 2.4–9.3  $\mu\text{m}$  wavelength range," *Appl. Phys. Lett.*, vol. 88, p. 041122, 2006.
- [9] L. Xue, S. R. J. Brueck, and R. Kaspi, "CW, high power, single-longitudinal-mode operation of an optically pumped midIR DFB laser," in *CLEO/QELS and PhAST 2007 Tech. Dig.*, Washington, DC, 2007, Optical Society of America, Paper CMFF4.
- [10] I. Vurgaftman *et al.*, "Far-field characteristics of midinfrared angled-grating distributed feedback lasers," *J. Appl. Phys.*, vol. 88, pp. 6997–7005, 2000.
- [11] R. Q. Yang *et al.*, "Continuous-wave operation of distributed feedback interband cascade lasers," *Appl. Phys. Lett.*, vol. 84, pp. 3699–3701, 2004.
- [12] C. S. Kim *et al.*, "Single-mode distributed-feedback interband cascade laser for the midwave infrared," *Appl. Phys. Lett.*, vol. 88, p. 191103, 2006.
- [13] J. R. Marciano and G. P. Agrawal, "Nonlinear mechanisms of filamentation in broad-area semiconductor lasers," *J. Appl. Phys.*, vol. 32, pp. 590–596, 1996.
- [14] S. A. Anson, J. T. Olesberg, M. E. Flatte, T. C. Hasenberg, and T. F. Boggess, "Differential gain, differential index, and linewidth enhancement factor for a 4  $\mu\text{m}$  superlattice laser active layer," *J. Appl. Phys.*, vol. 86, pp. 713–718, 1999.
- [15] M. Lerttamrab, S. L. Chuang, R. Q. Yang, and C. J. Hill, "Linewidth enhancement factor of a type-II interband-cascade laser," *J. Appl. Phys.*, vol. 96, pp. 3568–3570, 2004.