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## ABSTRACT

A broadly tunable, high power, continuous-wave, infrared laser suitable for molecular spectroscopy has been developed. The gain medium, based on type-II InAs:GaSb quantum wells, is adjustable from 2.5- to 12- $\mu\text{m}$  by adjusting the quantum well thicknesses. Tuning is achieved with a chirped distributed feedback grating, providing a simple, single adjustment tuning over an extended range. A tuning range of 65 nm has been achieved; much larger tuning ranges are possible, making the entire IR accessible with a small number of devices.

## II.A OBJECTIVE

The objective of this program was to develop high-power, CW, continuously tunable, broad spectral range, semiconductor lasers suitable for atmospheric pressure gas phase spectroscopy.

## II.B BACKGROUND

Spectroscopic applications such as chemical and biological remote sensing in the infrared spectral region require a tunable, cw high power laser source with a narrow spectrum. Typical small molecule absorption linewidths at atmospheric pressure are  $\sim 1\text{ cm}^{-1}$ . Remote detection and discrimination of these characteristic linewidths at a distance requires a bright (power/steradian/Hz) source. Broadband (thermal) sources are insufficiently bright. Typical laser sources have useful brightness, but lack the ready tunability to unambiguously identify species and to rapidly slew across wide wavelength ranges. Despite many years of effort, a convenient rapidly tunable infrared laser system that can cover the entire infrared molecular fingerprint region has yet to be developed.

Optically pumped type-II GaSb:InAs based lasers can be structurally adjusted, by changing the quantum well structure, across the entire 2.4- to 12- $\mu\text{m}$  wavelength range and have demonstrated output powers up to 11 W at 77K.<sup>1</sup> Distributed feedback (DFB) lasers have proven to be a reliable and economical way to narrow semiconductor laser spectra. Using these laser sources, we have demonstrated single-longitudinal-mode operation, narrow linewidth of 0.2 nm and record cw output power of 560 mW from a DFB laser at 3.6

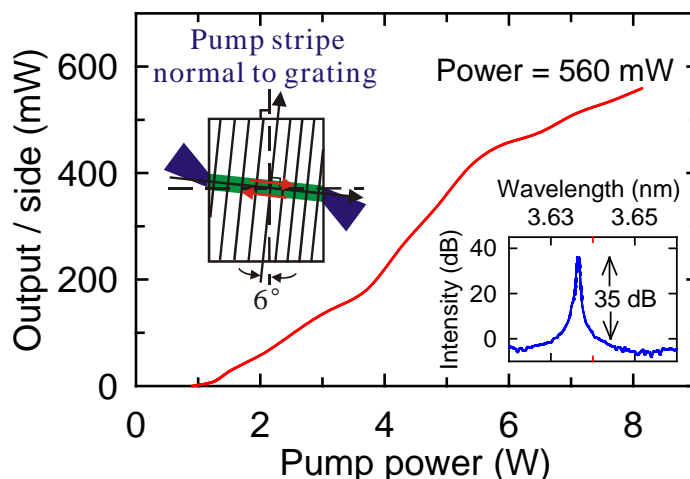


Fig. 1: Output power of an optically-pumped tilted stripe GaSb:InAs quantum well laser at 3.6  $\mu\text{m}$ . Single mode output is achieved up to  $\sim 0.5$  W (double sided).

$\mu\text{m}.$ <sup>2</sup> [Fig. 1]

In this program, we fabricated a novel chirped-grating DFB and achieved 65 nm of continuous wavelength tuning in a 3-mm-high by 2.5-mm-wide DFB laser device and demonstrated methane absorption spectra.<sup>3</sup> The basic tuning idea is to chirp the grating so that shifting the pump stripe position on the wafer results in a shifted wavelength. Then continuous tuning is available with a single adjustment (in contrast to most tunable semiconductor lasers that require two adjustments to track the material gain and the laser cavity mode). The demonstrated tuning range of 65 nm is the largest ever achieved in a single device with a simple single parameter tuning.

Spectroscopic measurements of unbuffered methane ( $\text{CH}_4$ ) gas were conducted using the chirped-grating DFB laser as a tunable light source. A 10-cm gas cell was placed in the path of the DFB laser beam. The transmittance spectra of methane was obtained by recording the signal from the InSb photodiode after the gas cell, divided by the signal from the InSb photodiode before the gas cell, as the laser wavelength was tuned in 0.02-nm steps by mechanical translation of

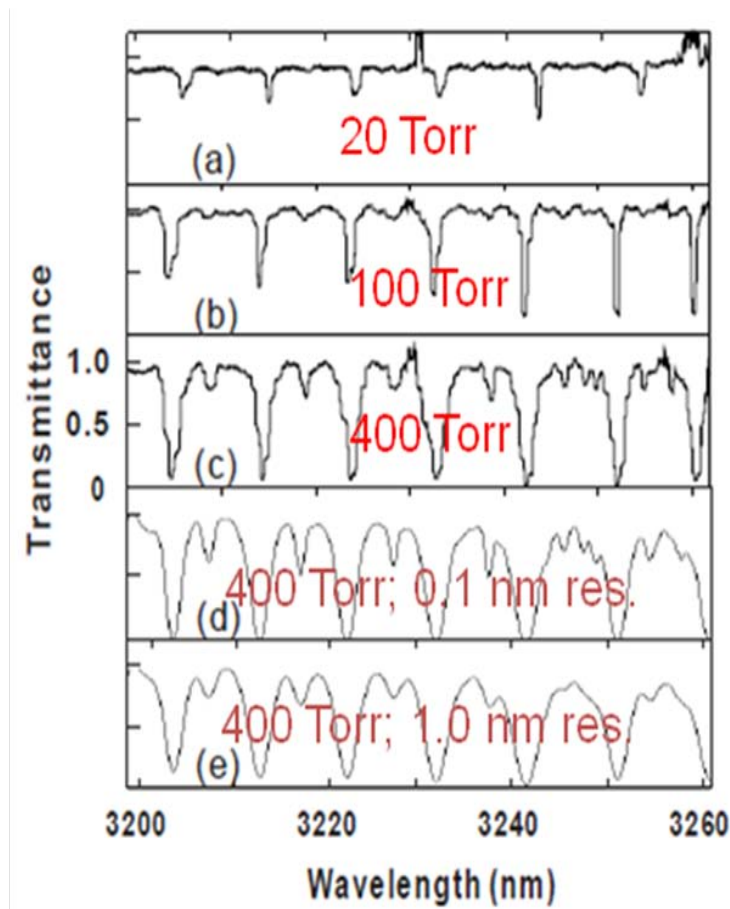


Fig. 2:  $\text{CH}_4$  spectroscopic demonstration. The top three traces are experimental at the pressures indicated (10 cm path length). The bottom two traces are HITRAN simulations verifying the spectral linewidth of  $\sim 0.5$  nm.

the laser chip relative to the fixed pump stripe. The transmittance spectra of methane at different pressures are shown in Fig. 2(a) – (c). A comparison between the experimentally obtained methane transmittance spectrum at 400 torr (Fig. 3(c)) and HITRAN simulations using different laser linewidths (Fig. 2(d) and (e)) suggests a DFB laser linewidth between 0.1 and 1 nm, in agreement with the measured linewidth of  $\sim 0.6$  nm. Careful examination of the methane transmittance spectrum reveals step-like features with a width of 0.56 nm, the same as the F-P cavity mode interval for the 2.5-mm-long cavity, showing that the peak of the laser spectrum hops among F-P modes during tuning. The wavelength tuning is therefore classified as quasi-continuous. Since the laser linewidth is comparable to the F-P spacing, continuous frequency coverage is obtained. The experimental linewidth is large in comparison

with other DFB lasers as a result of the absence of transverse structural mode control (e.g. a ridge), the wide pump stripe, and the low confinement associated with the large-optical cavity design. The tradeoff for this weak transverse/lateral confinement is higher SLM output power and suppression of filamentation. The experimental linewidth is quite suitable for atmospheric-pressure molecular spectroscopy.

The gratings are fabricated at a slight tilt ( $6^\circ$ ) to the facets to eliminate facet reflectivity into the DFB cavity. Since these lasers are optically pumped, the pump stripe can be aligned either along the grating normal or along the facet normal. For the power output measurements (Fig. 1) a conventional DFB (stripe normal to the grating lines) was used. For the tuning measurements, an  $\alpha$ -DFB configuration with the pump stripe aligned along the facet normal was used because of the larger feedback and more robust lasing in this configuration. In this configuration, the facet Fabry-Perot modes contribute to the lasing and the tuning is characterized by a longitudinal mode hopping at a spacing of 0.6 nm for this 2.5 mm long cavity. This is seen more clearly in an expanded spectral scan as shown in Fig. 3. Since this spectral gap is less than the  $\sim 1$ -nm laser linewidth and the comparable pressure broadened  $\text{CH}_4$  spectral linewidth at atmospheric pressure, all of the lines are observed and this quasi continuous tuning is sufficient for molecular identification and quantification.

However, for the most utility, it will be necessary to achieve a true continuous tuning without any mode hops. Part of the difficulty in achieving this has been the low confinement (index contrast between the gain and cladding regions) deliberately built into these large optical cavity devices. There is a trade-off between the single mode power and the achievable coupling. A full understanding of this tradeoff and of the dynamic behavior of this novel tuning mechanism is the objective of the first year of this program. Initial work will be carried out in the near-IR around the C-H stretch spectral region, which is not well covered by other tunable laser sources such as quantum cascade lasers. In later phases of the program these lasers will be extended to longer wavelengths to cover important spectral features such as the phosphorous-oxygen stretch around  $10\ \mu\text{m}$  characteristic of many nerve agents. As the program progresses, we will discuss the optimum wavelength for Air Force needs with Air Force personnel.

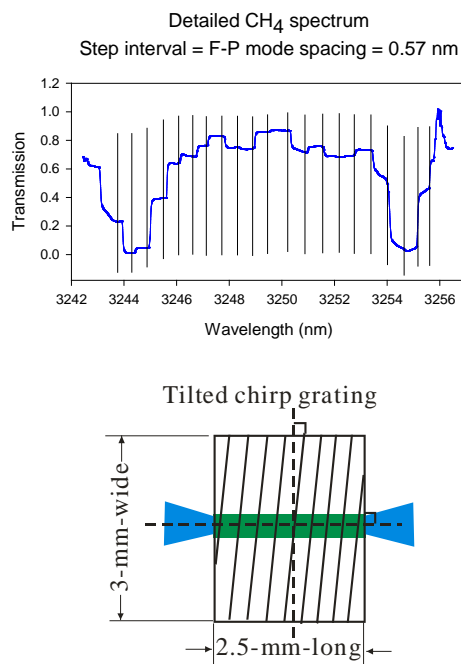


Fig. 3: Expanded spectral scan showing the step like wavelength shifts associated with the longitudinal Fabry-Perot modes of the  $\alpha$ -DFB cavity (pump stripe perpendicular to facets).

An important feature of the type-II InAs:GaSb quantum-well system is that the gain can be shifted across the entire infrared (2.5 to 12  $\mu\text{m}$ ) simply by adjusting the quantum well dimensions. This provides a very convenient technique to both set the center frequency and adjust the gain bandwidth. Multiple quantum well gain regions can be incorporated into a single laser mode volume to provide a larger gain bandwidth and hence a larger tuning range in a single device. Again, there are multiple tradeoffs that have to be carefully investigated and understood in order to optimize these devices. In particular, absorption in longer wavelength quantum wells can impact the lasing with gain provided by shorter wavelength quantum wells.

The chirped grating is a novel laser element that is not completely understood. Inevitably, connected with the desired chirp that provides the tuning mechanism, there is a transverse grating chirp across the mode and a longitudinal chirp from one end of the cavity to the other. The impact of these chirps on the spectral output of the laser is not fully understood at present. This of course impacts the magnitude of the chirp that can be tolerated for a given laser, and therefore the size of the chip for a given tuning range. In future work, a detailed analytical study of the impact of these DFB grating chirps will be carried out and correlated with experiments. We have previous experience with both analytic coupled mode analysis and finite-difference time-domain (FDTD) simulations for a number of nanophotonic devices.

The need for a high brightness CW molecular spectroscopy source extends to many commercial and other DoD applications. The devices developed in this program will find many applications. A tunable, high power, high brightness laser source for infrared molecular spectroscopy represents both important new laser device physics and urgent applications.

<sup>1</sup> 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. **88**, 041122 (2006).

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# Widely tunable distributed-feedback lasers with chirped gratings

Liang Xue,<sup>1,a)</sup> S. R. J. Brueck,<sup>1,b)</sup> and R. Kaspi<sup>2,c)</sup>

<sup>1</sup>Department of Electrical and Computer Engineering and Center for High Technology Materials, University of New Mexico, Albuquerque, New Mexico 87106, USA

<sup>2</sup>Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base, Albuquerque, New Mexico 87117, USA

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A quasicontinuous tuning range of 65 nm at 3.2  $\mu\text{m}$  was obtained for continuous wave, single-longitudinal-mode operation at 77 K of an optically pumped distributed-feedback laser with a chirped grating. Interferometric lithography with spherical wavefronts was used to fabricate a large-area chirped grating whose period varied continuously in the direction of the grating lines. Tuning was achieved by translating the optical pump stripe relative to the device to activate regions with different grating periods. Methane absorption spectra, obtained using this tunable distributed-feedback laser, closely match the high-resolution transmission molecular absorption database simulations. © 2009 American Institute of Physics. [DOI: 10.1063/1.3123813]

The mid-IR (3–5  $\mu\text{m}$ ) atmospheric transmission window is important for spectroscopic applications because it contains many fundamental molecular absorption lines including the C–H stretch at  $\sim 3.3 \mu\text{m}$ . Many spectroscopic applications require a continuous wave (cw), single-longitudinal-mode (SLM), widely tunable, high-power laser source. Recently, we have reported an optically pumped type-II distributed feedback (DFB) laser with high output power ( $>560 \text{ mW/facet}$ ) in a cw SLM operation at 3.64  $\mu\text{m}$ .<sup>1</sup> However, the thermal tuning range of that device was only  $\sim 6.8 \text{ nm}$  limited by the laser performance at higher temperatures. The thermal tuning ranges of intersubband quantum cascade<sup>2</sup> and interband cascade<sup>3</sup> DFB lasers are generally limited to  $<20 \text{ nm}$  ( $0.5\% \Delta\lambda/\lambda$ ). Tuning range enhancing technologies such as superstructure gratings DFB (Ref. 4) and selectable DFB arrays<sup>5</sup> can extend the tuning range to  $\sim 10\% \Delta\lambda/\lambda$ . However, both of these technologies require rather complex laser structures and tuning protocols. In this paper, we report a tuning method using a chirped DFB grating that is easily fabricated using spherical-wavefront interferometric lithography (IL). A quasicontinuous tuning range of 65 nm ( $2\% \Delta\lambda/\lambda$ ) was obtained from a 3.5 mm wide chirped-grating DFB laser for cw SLM operation at 3.2  $\mu\text{m}$ . Spectroscopic experiments using the tunable DFB laser as a light source yield methane absorption spectra that closely match high-resolution transmission molecular absorption (HITRAN) simulations.

The type-II laser device was grown by molecular beam epitaxy.<sup>6</sup> It consists of a GaSb:Te substrate (index  $n_{\text{sub}}=3.82$ ), a 1.5  $\mu\text{m}$  thick active region ( $n_{\text{active}}=3.84$ ) consisting of 14 type-II InAs/InGaSb/InAs W-quantum wells, and a 1.5  $\mu\text{m}$  thick top clad layer ( $n_{\text{clad}}=3.82$ ). A 500 nm thick, high-index germanium (Ge) layer ( $n_{\text{Ge}}=3.99$ ) was deposited on the top clad to increase the modal confinement in the active region. A 450 nm deep chirped grating was fabricated in the Ge layer using IL and inductive coupled plasma etching, giving a coupling coefficient  $\kappa \sim 4 \text{ cm}^{-1}$ .

A planoconvex lens (focal length  $f=37.8 \text{ mm}$ ) was used in IL to transform the plane wavefronts of the 355 nm laser into spherical wavefronts, as shown in Fig. 1(a). The interference pattern is therefore a series of hyperbolae,<sup>7</sup> [Fig. 1(b)] that provide a chirp of the grating period along the device. The grating was deliberately tilted  $6^\circ$  relative to the facet in order to suppress the Fabry–Perot (FP) modes when the pump stripe is perpendicular to the grating.<sup>1</sup> The wafer was then lapped to a thickness of 150  $\mu\text{m}$ . A  $2.5 \times 3.5 \text{ mm}^2$  device was cleaved and indium-soldered (active region up) to a copper heat sink mounted in a 77 K liquid nitrogen dewar. For the device with a cavity length  $L$  of 2.5 mm, the coupling strength is estimated to be  $\kappa L \sim 1$ . The grating period ranges from 425 to 435 nm (3%) in the lateral direction (parallel to the grating), corresponding to a DFB wavelength from 3200 to 3270 nm. There is also a 0.2% period chirp in the longitudinal direction (perpendicular to the grating) between the center and edge of the device. This longitudinal chirp introduces a continuously distributed phase shift in the grating.<sup>8</sup>

A 1908 nm cw fiber laser source was used to illuminate an 80  $\mu\text{m}$  wide stripe across the device, providing both laser gain and lateral mode guiding. The device worked well only when the pump stripe was oriented perpendicular to the facet, because the grating, with a small  $\kappa L$ , did not provide sufficient optical feedback without the help of facet reflection. In this configuration, there is a  $6^\circ$  tilt between the pump stripe and the grating, similar to a tilted-ridge DFB laser.<sup>9</sup> Due to the facet reflection, there remains an influence of the

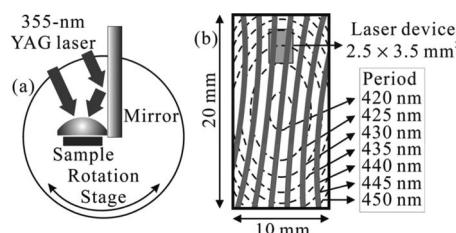


FIG. 1. (a) The spherical wavefront IL arrangement for chirped gratings; and (b) the  $6^\circ$  tilted hyperbolic chirped grating (solid lines) and the elliptic period contour (dashed lines). The position of the laser material during the exposure is indicated.

<sup>a)</sup>Electronic mail: xueliang@chtm.unm.edu.

<sup>b)</sup>Electronic mail: brueck@chtm.unm.edu.

<sup>c)</sup>Electronic mail: ron.kaspi@kirtland.af.mil.



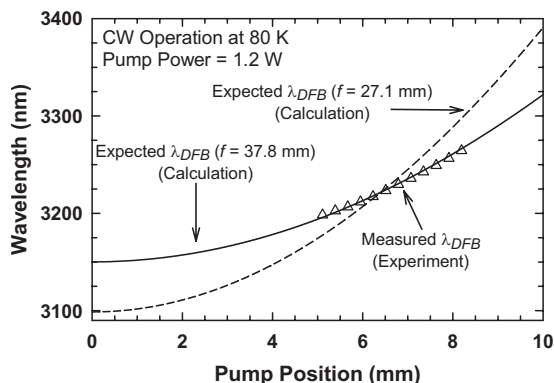


FIG. 2. Expected chirped-grating DFB tuning curves based on the focal length  $f$  of the lens used for the IL. Dashed line for  $f=27.1$  mm and solid line for  $f=37.8$  mm. Triangles represent the measured wavelengths.

FP modes on the laser spectrum. At lower pump powers, (up to about four times threshold) the laser exhibits SLM emission, with the peak of the DFB mode always located at the wavelength of the nearest FP mode. At higher pump powers, there is significant energy contained in FP modes at the peak of the gain spectrum that are independent of the grating.

The DFB laser emission was directed into a 1/2-m monochromator with a spectral resolution of 0.2 nm, and recorded by a 77 K InSb photodiode with standard signal processing electronics. The spectra of the laser were recorded as the device was translated relative to a fixed pump stripe. A 65 nm tuning range was achieved at a fixed pump power of 1.2 W ( $1.7 \times$  threshold) where the SLM wavelength is controlled by the grating (Fig. 2). A tuning rate of 18.6 nm/mm is obtained, as indicated in Fig. 2. This was controlled by the focal length of the lens used for the IL. A gear-reduced stepper motor, with a position step corresponding to a tuning of 0.002 nm was used to adjust the laser position relative to a fixed pump stripe (and collection optics). The laser linewidth was  $\sim 0.6$  nm and the output power was  $\sim 30$  mW. The potential tuning range, limited by the grating fabrication, for a 10-mm-long device, is  $\sim 170$  nm using a 37.8 mm focus lens in IL, and  $\sim 300$  nm using a 27.1 mm focus lens in IL. At a fixed pump stripe position near the center of the device, the maximum cw output power was  $\sim 560$  mW/facet (including the nongrating-related FP emission peaks) while the maximum cw SLM output power was  $\sim 200$  mW/facet.

Spectroscopic measurements of unbuffered methane ( $\text{CH}_4$ ) gas were conducted using the chirped-grating DFB laser as a tunable light source. A 10 cm gas cell was placed in the path of the DFB laser beam. The transmittance spectra of methane was obtained by recording the signal from the InSb photodiode after the gas cell, divided by the signal from the InSb photodiode before the gas cell, as the laser wavelength was tuned in 0.02 nm steps by mechanical translation of the laser relative to the fixed pump stripe. The transmittance spectra of methane at different pressures are shown in Figs. 3(a)–3(c). A comparison between the experimentally obtained methane transmittance spectrum at 400 torr [Fig. 3(c)] and HITRAN simulations using different laser linewidths [Figs. 3(d) and 3(e)] suggests a DFB laser linewidth between 0.1 and 1 nm, in agreement with the measured linewidth of  $\sim 0.6$  nm. Careful examination of the methane transmittance spectrum reveals steplike features with a width

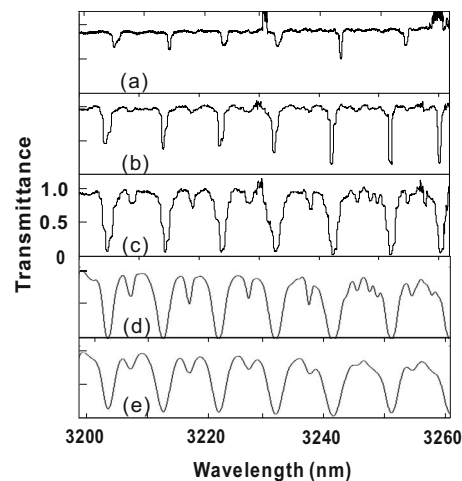


FIG. 3. [(a)–(c)] Experimentally obtained transmittance spectra of methane at 20, 100, and 400 torr, respectively; [(d) and (e)] HITRAN simulations of methane spectra at 400 torr for a laser linewidth of 0.1 and 1 nm, respectively.

of 0.56 nm, the same as the FP cavity mode interval for the 2.5-mm-long cavity, showing that the peak of the laser spectrum hops among FP modes during tuning. The wavelength tuning is therefore classified as quasicontinuous. Since the laser linewidth is comparable to the FP spacing, continuous frequency coverage is obtained. The experimental linewidth is large in comparison with other DFB lasers as a result of the absence of transverse structural mode control (e.g., a ridge), the wide pump stripe, and the low confinement associated with the large-optical cavity design. The tradeoff for this weak transverse/lateral confinement is higher SLM output power and suppression of filamentation, but with a larger linewidth. The experimental linewidth is quite suitable for atmospheric-pressure molecular spectroscopy.

In summary, we have demonstrated cw SLM operation of an optically pumped, type-II, chirped-grating laser with a 65 nm quasicontinuous tuning range at  $3.2 \mu\text{m}$ . Methane spectroscopy experiments using this tunable laser closely match HITRAN simulations. If a 27.1 mm focus lens had been used in IL, the period chirp of a 10-mm-wide device would have been  $\sim 40$  nm, corresponding to a potential tuning range of  $\sim 300$  nm at  $3.2 \mu\text{m}$  ( $\Delta\lambda/\lambda \sim 10\%$ ). A two-partition optically pumped type-II laser incorporating two different sets of quantum wells has been recently developed.<sup>10</sup> The same design can be used in a nonpartitioned device to provide an extended gain bandwidth ( $\sim 500$  nm) to support the broad tuning range of the chirped DFB design.

Two directions for improving the tuning are immediately evident. A longer device would further reduce the FP mode spacing, which is already comparable to atmospheric-pressure-broadened molecular linewidths, insuring that all lines are captured. Alternatively, the mode hopping among FP modes during tuning can be avoided by orienting the pump stripe perpendicular to the grating, provided that a larger  $\kappa L$  can be obtained. Work is underway to investigate higher confinement epitaxial designs that should provide continuous and smoothly tunable frequency coverage.

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The HITRAN simulations were provided by Dr. Dennis Killinger at the University of South Florida.

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

L. Xue, S. R. J. Brueck, *Fellow, IEEE*, and R. Kaspi

**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

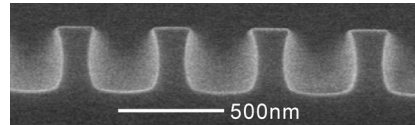


Fig. 1. Cross-sectional scanning electron microscope picture of the DFB grating.

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

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L. Xue and S. R. J. Brueck are with the Center for High Technology Materials, University of New Mexico, Albuquerque, NM 87106 USA (e-mail: xueliang@unm.edu).

R. Kaspi is with the Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base, Albuquerque, NM 87117 USA.

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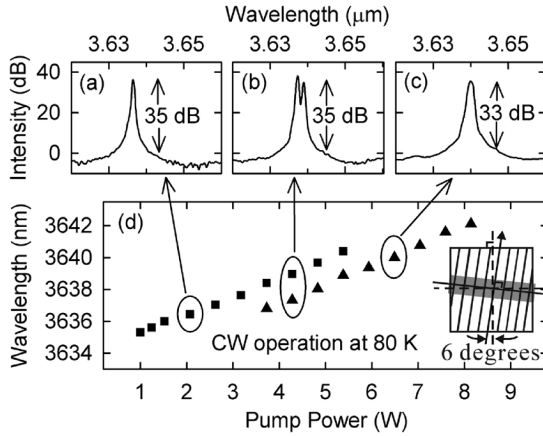


Fig. 2. (a)-(c) DFB spectra under pump power of 2, 4.2, and 6.5 W, respectively. (d) Lasing wavelength of the DFB laser working at 80 K.

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.

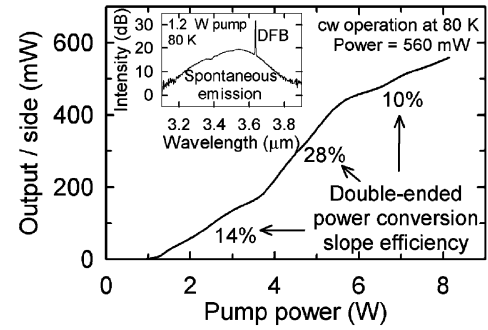


Fig. 3. Single-ended output power versus pump power of the DFB laser. Inset is the spontaneous emission spectrum collected from the top of the device.

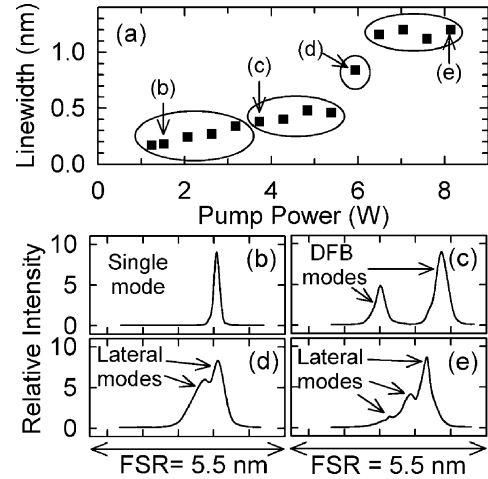


Fig. 4. (a) Linewidth of the DFB laser for CW operation at 80 K. (b)-(e) Laser spectra measured with F-P interferometer.

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 was 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.

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