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BIG LIGHT: OPTICAL COHERENCE OVER VERY LARGE AREAS IN PHOTONIC-CRYSTAL DISTRIBUTED-FEEDBACK LASERS

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Introduction: High-power midwave-infrared (mid-IR) semiconductor lasers, emitting in the $\lambda = 3 - 5 \mu\text{m}$ wavelength range, are needed to jam heat-seeking-missile threats to U.S. planes and ships. Because of their potential for compactness and low-cost, they are viewed as ideal long-term sources for infrared countermeasure (IRCM) systems. The most straightforward way to scale up the output power is to widen the stripe of gain material that is lasing. However, this strategy is usually ineffective because optical coherence is generally lost once the stripewidth exceeds a few wavelengths. The beam then tends to break into multiple modes, or filaments, that lase independently of one another, rather than maintaining optical coherence over the entire gain region. The result is a rapidly diverging output beam that becomes much too diffuse to be useful when it reaches a missile nosecone several kilometers away.

Device Concept: NRL has recently developed a new class of semiconductor lasers that maintain an exceptional degree of optical coherence over very large device areas. This is the photonic-crystal distributed-feedback (PCDFB) laser, shown schematically in Fig. 1 with an overlaid scanning electron micrograph (SEM) of one of the patterned devices. A two-dimen-

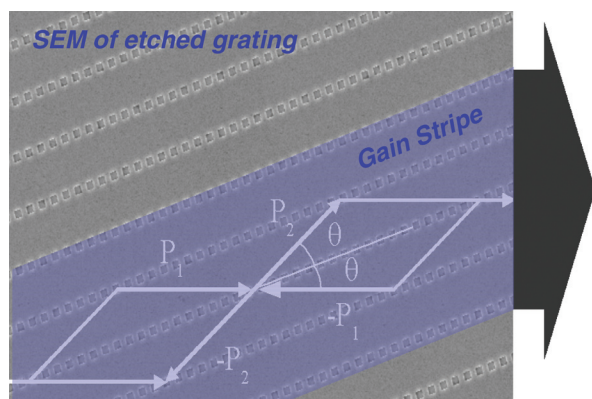


FIGURE 1 Schematic of the major propagation directions and the alignment with the facets for a rectangular-lattice PCDFB laser, overlaid with a scanning electron micrograph of the etched 2D grating.

sional (2D) rectangular grating is etched into the tilted gain stripe to diffract the lasing mode propagating along the directions P_1 , $-P_1$, P_2 , and $-P_2$. For example, the grating reflects light that was originally propagating along P_1 into the opposite direction $-P_1$, and also simultaneously diffracts it by angles of $\pi - 2\theta$ and 2θ into the directions P_2 and $-P_2$. The first process is analogous to the distributed feedback mechanism (DFB) that induces strong spectral selectivity in conventional 1D DFB lasers. The other two processes diffractively couple regions of the gain medium that are widely separated spatially. The net result is that optical coherence is imposed over the entire gain stripe, which can now be very wide, whereas the diffractive propagation strongly suppresses the usual tendency of the mode to collapse into narrow filaments. This is accomplished with a modest penalty in the device's quantum efficiency (roughly a factor of two). Our numerical simulations project that for any given semiconductor material system, the PCDFB configuration should produce more power in a spectrally pure single mode than any other configuration.¹ The PCDFB geometry is applicable to semiconductor lasers emitting at wavelengths extending from the ultraviolet to the Terahertz regime.

Practical Realization of the Edge-Emitting PCDFB Laser: Our first experimental demonstrations of the PCDFB laser concept have used optically pumped antimonide type-II “W” quantum well active regions that emit in the mid-IR.² For the device shown in Fig. 1, a second-order grating with $\theta = 16^\circ$ was defined in a top GaSb layer by electron-beam lithography and reactive ion etching. By tuning the operating temperature of the laser, the peak of its gain spectrum was brought into resonance with the grating wavelength of $\lambda \approx 3.7 \mu\text{m}$. The solid blue curve of Fig. 2 illustrates the far-field profile measured for this PCDFB laser when a 350- μm -wide stripe was pumped in pulsed mode at 10 times the lasing threshold.³ Note that even though the stripewidth exceeds the wavelength by two orders of magnitude, the profile has a single lobe with an extremely narrow angular divergence of 0.8° full-width at half-maximum (FWHM). Since this corresponds to just over 3 times the theoretical minimum, the diffraction limit, it demonstrates that a high degree of optical coherence is maintained across the wide stripe. At a stripewidth of 150 μm , the output was basically diffraction-limited, and even for a 600- μm stripe the profile retained a single lobe with only slightly greater divergence (1.2° FWHM). By contrast, the dashed red curve shows the analogous result for a typical unpatterned Fabry-Perot laser fab-

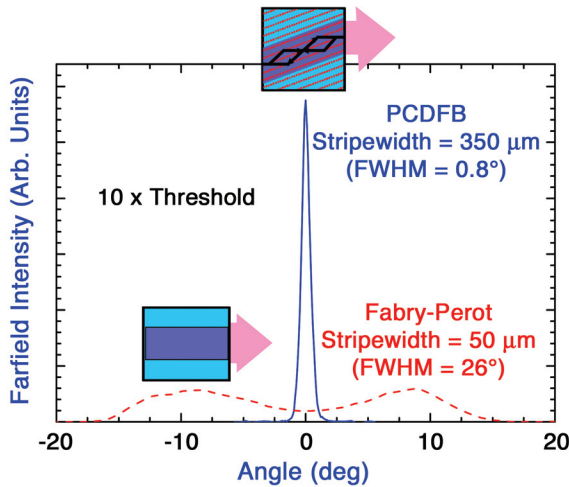


FIGURE 2 Far-field profiles for a mid-IR PCDFB laser with stripwidth 350 μm (solid blue) and a typical Fabry-Perot laser with stripwidth 50 μm (dashed red). Both were optically pumped at 10 times the lasing threshold.

ricated from similar material with a pump stripwidth of only 50 μm . In that case, the total divergence angle of the double-lobed far-field profile is 26°. Without the PCDFB grating, the beam quality is quite poor because optical coherence is lost when no mechanism exists for coupling the widely separated lateral regions of the stripe. These PCDFB results are far superior to any reported previously for such wide stripes in the mid-IR, making this approach quite promising for IRCM applications.

Surface-Emitting PCDFB Lasers: In the “edge-emitting” geometry discussed above, the output is extracted from a cleaved facet whose reflectance also helps to define the cavity. Since the output aperture is much wider laterally than along the growth direction (into the page of Fig. 1), most edge-emitting semiconductor lasers produce a highly elliptical beam that requires further shaping before it is useful. However, we have designed and fabricated a surface-emitting (SE) version⁴ of the PCDFB laser, whose fundamental mode yields a circularly symmetric output. Figure 3 illustrates schematically that a hexagonal 2D grating again imposes optical coherence over a broad lateral area via diffraction of the in-plane lasing mode. In

this case, there are no facets and the output is emitted normal to the wafer surface by an additional diffraction process, indicated by the red arrow. Mid-IR SE PCDFB lasers with optically pumped type-II “W” active regions were recently fabricated and tested in the laboratory. The near-field IR camera picture shown as the inset in Fig. 3 indicates a beam profile with nearly circular symmetry. Beam divergences as small as ≈ 6 times the diffraction limit have been observed for a pump-spot diameter of 800 μm . This provides further evidence for strong optical coherence over extremely large areas.

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- ³ C.S. Kim, W.W. Bewley, C.L. Canedy, I. Vurgaftman, M. Kim, and J.R. Meyer, *IEEE Phot. Tech. Lett.* **16**, 1250-1252 (2004).
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FIGURE 3 Hexagonal-lattice surface-emitting PCDFB laser, showing major propagation directions. The experimental near-field profile (taken with an IR camera) shown as the inset indicates the near-circular symmetry of the output beam.

