Microlenses Stabilize Microchip VECSELs

Diamond microlenses serve as both heat spreader and output coupler.

Vertical external-cavity surface-emitting lasers (VECSELs) have proved useful in numerous applications because they can be readily fabricated to produce various wavelengths and, unlike their edge-emitting cousins, produce a round collimated beam.

Although vertical-cavity surface-emitting lasers (VCSELs) are monolithic with both (plane) resonator mirrors integrated into the semiconductor chip, VECSELs have a separate (external) output coupler. Because the external optics of a VECSEL allow focusing or wavelength selectivity to be added to the resonator design, VECSELs are generally more versatile than VCSELs.

However, although the external output coupler brings increased versatility, it compromises the robustness compared with monolithic devices. Recently, scientists from the Institute of Photonics at the University of Strathclyde in Glasgow, UK, have bonded diamond microlenses to vertical-emitting laser chips, producing a pseudomonolithic VECSEL that blurs somewhat the meaning of the word "external" in the VECSEL designation — but that, in essence, provides the best of both worlds.

The diamond microlenses serve as the lasers' output couplers and provide the intracavity focusing that diminishes pump-induced thermal instabilities. A resonator with two plane reflectors and no intracavity focusing cannot support a stable oscillating mode because, in effect, there's nothing to keep the light from leaking out around the edges of the reflectors. In a VCSEL, with two plane reflectors, pump-induced thermal lensing provides the necessary focusing, but the strength of the thermal lensing depends on pump power. Thus, the quality of the output beam varies significantly with pump power.

This variation can be reduced greatly by adding an output coupler that provides intracavity focusing, as the scientists at Strathclyde have done. And, because diamond has exceptionally good thermal conduc-

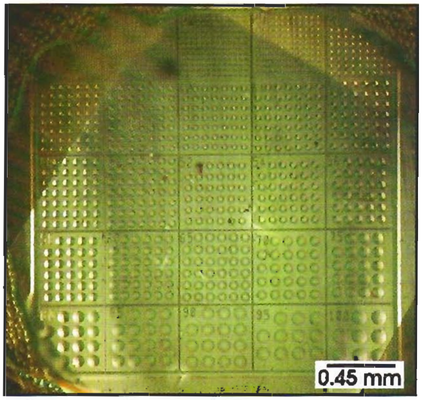
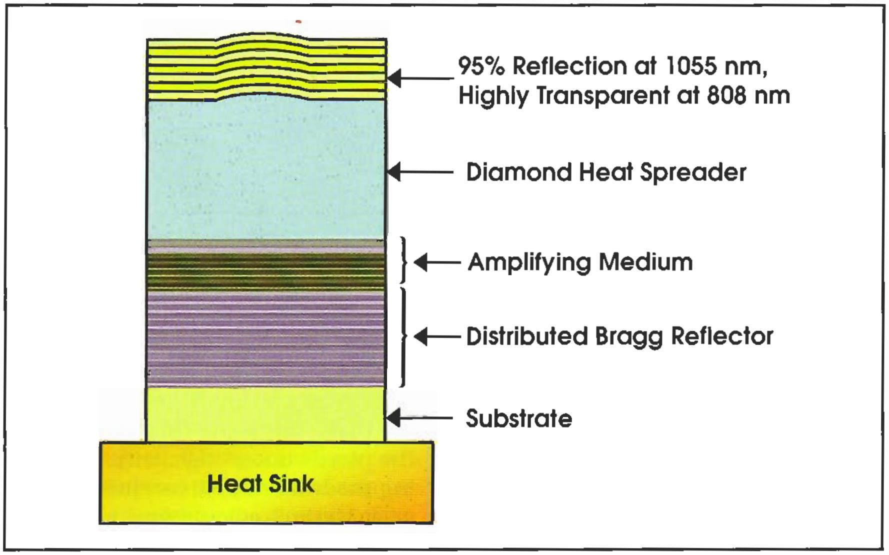


Figure 1. Scientists capillary-bonded a microlens array with lenses of various sizes onto a semiconductor chip (above). The radius of curvature of each microlens — and hence its focusing power — varied with the diameter (right). Images reprinted with permission of *Optics Express.*



tivity, the capillary-bonded microlens acts as a heat spreader, diminishing the deleterious effect of pump-induced thermal gradients.

The scientists fabricated arrays of VECSELs with various sizes of microlenses and carefully characterized the performance of lasers with different lenses (Figure 1). They focused pump light from an 808-nm fiber-coupled diode laser into the individual VECSELs one at a time and measured that laser's input-vs.-output transfer function, its beam quality (M^2) and its spectrum.

They found that the input-vs.-

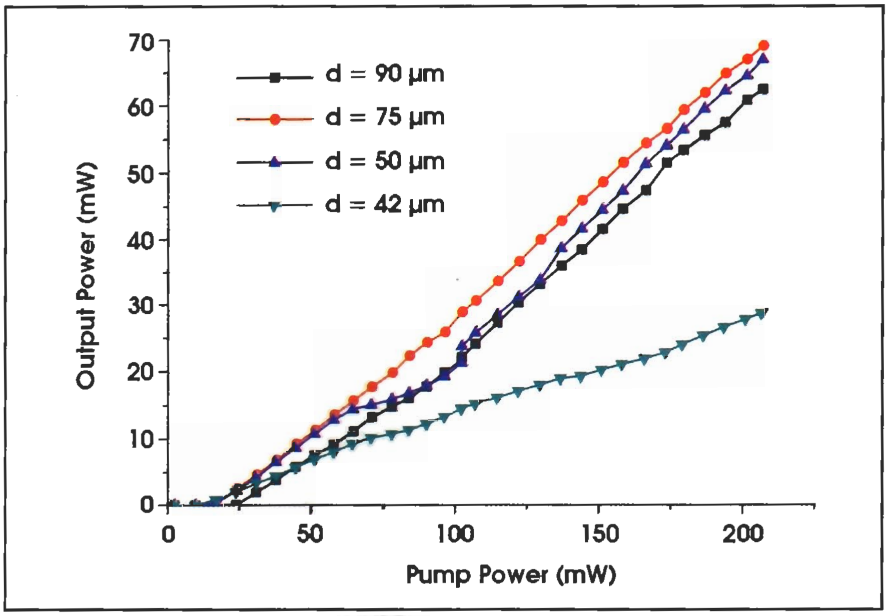


Figure 2. The inferior performance of the laser with the smallest microlens results from poor coupling between the pump light and the lowest-order laser mode, combined with high aperture losses of higher-order modes.

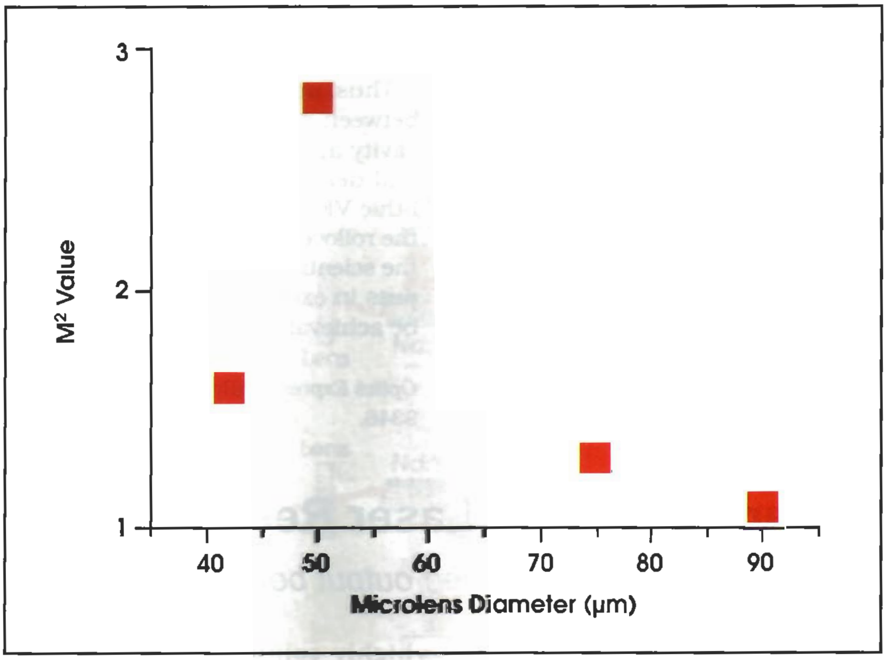


Figure 3. The lasers' beam quality decreased (i.e., M^2 increased) as the microlens diameters decreased from 90 to 50 µm, a result of diminishing physical overlap between the TEM_{00} mode and the intracavity pump power. But the smallest microlenses acted as intracavity apertures, forcing high-order modes below threshold.

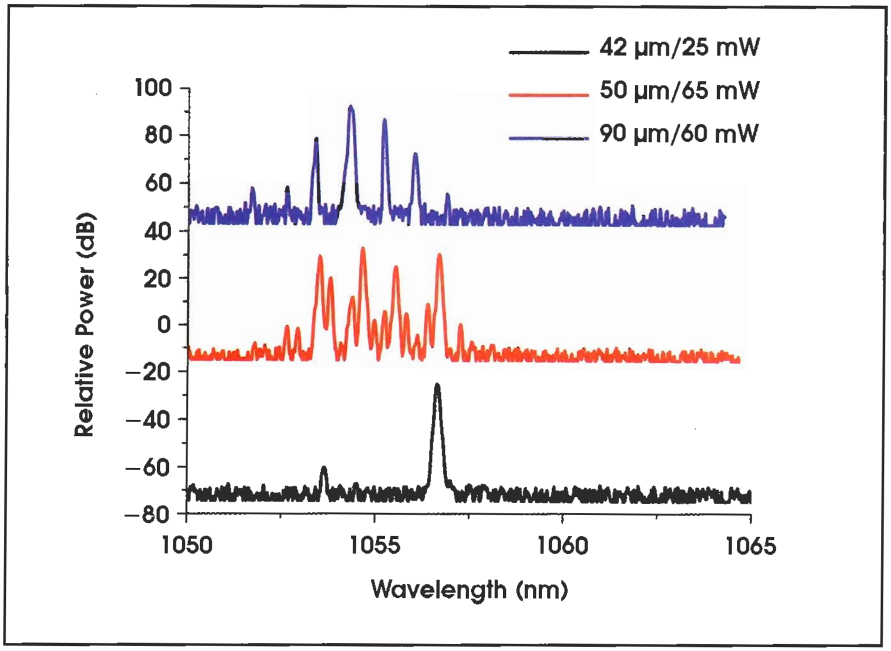


Figure 4. The lasers' spectra show that multiple transverse modes oscillate with a 50-μm-diameter mirror.

output characteristics didn't depend much on the size of the microlens, except for the smallest (42 μm diameter) lens (Figure 2). To explain why, they calculated the size of the intracavity TEM_{00} mode and the size of the pump beam inside the resonator. They attribute the low performance with the smallest microlens to a combination of two unfavorable conditions.

First, the 42-μm-diameter output coupler focused the intracavity TEM_{00} mode to a size much smaller than the pump light, so that mode could utilize only a fraction of the pump power. Higher-order transverse modes are bigger and can utilize the pump power more effectively, but the small diameter of the output coupler — that is, the 42-μm-diameter microlens — acted as a resonator aperture, introducing so much loss to the high-order modes that they never reached threshold.

The scientists saw further evidence of the interplay between these two factors — mode matching and resonator aperturing — when they measured the beam quality of lasers with different microlenses (Figure 3). For the larger microlenses — that is, those with weaker intracavity focusing — the TEM_{00} mode was loosely focused and matched well with the intracavity pump beam. In these cases, the TEM_{00} mode was preferentially excited, and high-quality beams ($M^2 < 1.3$) emerged from those lasers.

As the lenses got smaller, they focused the intracavity laser modes more tightly, so that higher-order modes were better matched to the size of the pump beam and could reach threshold. Note in Figure 3 that, as the lens diameter decreased from 90 to 50 μm, the beam quality decreased from M^2 ~1.1 to ~2.8.

However, as the microlenses got even smaller, the aperturing effect came into play. The laser with the smallest lens (42 μm diameter) had good beam quality not because the intracavity TEM_{00} mode matched the size of the pump beam, but because the small aperture prevented the higher-order modes from reaching threshold.

Finally, the lasers' spectra provided more clarity on the interplay between mode matching and aperturing (Figure 4). For the weakly focusing (largest) lenses, there was good matching between the TEM_{00} mode and the pump, and only the TEM_{00} mode oscillated.

These lasers' spectra showed only several clean, longitudinal modes of the fundamental transverse mode (top trace in Figure 4). The spectra of lasers with smaller lenses showed the multiple peaks of several transverse modes (middle trace). Finally, the smallest lens prevented the high-order transverse modes from reaching threshold, but the coupling between the TEM_{00} mode and the pump power was so weak that only a single longitudinal mode rose significantly above threshold (bottom trace).

Thus, understanding the interplay between mode matching and intracavity aperturing is the key to optimal design of these pseudomonolithic VECSELs. Extrapolating from the rollover-free outputs in Figure 2, the scientists believe that TEM_{00} outputs in excess of 100 mW soon will be achievable with these lasers. ☐

Breck Hitz

Optics Express, July 23, 2007, pp. 9341-9346.