High-brightness pump sources using 2D VCSEL arrays

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ABSTRACT

Many applications require laser pump sources with high output power (tens to hundreds of Watts) in the smallest spot, with the smallest divergence. Such high-brightness pump sources typically use edge-emitting semiconductor lasers. However, it is also possible to use high-power two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays for this purpose. Using a single 976nm 2D VCSEL array chip in an external cavity configuration, combined with a matching micro-lens array, we have demonstrated more than 30W output power from a 50μm/0.22NA fiber, corresponding to a brightness of 10MW/cm^2.sr. This represents a substantial reduction in module complexity compared to edge-emitter based modules with similar brightness. These novel high-brightness pump sources exhibit some well-known intrinsic VCSEL performance features such as wavelength stability and narrow spectrum. Power and brightness can be scaled up using polarization and spectral combining.

Keywords: semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs), high-power, 2D array, pumping, fiber-laser, solid-state laser, brightness, etendue, beam-quality, fiber coupling, 9xx nm, 808 nm

1. INTRODUCTION

There is a strong need for high-brightness lasers in the medical, industrial, and military fields. The brightness of a laser is its ability to produce the highest power, within the smallest spot and smallest divergence (units of W/cm^2.sr). The need is particularly strong for the material processing industry, where applications range from surface cleaning and treatment to marking, cutting, and welding.[1] High-brightness laser technologies include CO_2 lasers, diode-pumped solid-state (DPSS) lasers, diode-pumped fiber-lasers, and semiconductor lasers. The high-brightness semiconductor laser field is currently dominated by the edge-emitting laser technology. While high-brightness edge-emitter based modules are used directly in some applications (medical, printing, light material processing), they are also used indirectly in the optical pumping of solid-state or fiber-lasers to increase brightness (at the expense of power). In the case of fiber-lasers, several 9xx nm high-brightness edge-emitter-based pump modules are required to pump the fiber.[2] These edge-emitter modules typically output tens of Watts from a 100μm or 200μm core fiber.[3,4] By combining several of these modules, the output from the fiber can then reach up to several hundred Watts or even kW of power in a near diffraction limited beam.[5] As for DPSS lasers, in the case of Nd:YAG lasers for example, a high-brightness 808nm edge-emitter pump source can be used to produce a lower power 946nm or 1064nm beam, with better beam quality, resulting in increased brightness: in Ref. 6, an 808nm pump module with 31.6W output from a 400μm/0.22NA fiber (brightness of 165kW/cm^2.sr) is used to end-pump an Nd:YAG rod laser, producing 10.78W of 946nm light with a beam quality of 7.11, corresponding to a brightness of 24MW/cm^2.sr.

Besides brightness, high-power laser systems in the material processing industry are mainly characterized by CW power levels, spectral distribution, power conversion efficiency, and cost per Watt. While edge-emitter based approaches lag in brightness and power behind CO_2,[7] solid-state, and fiber-lasers, they have advantages in terms of cost and efficiency. For edge-emitter approaches, polarization and/or spectral combining can be used to scale up power and brightness[8] but while kW power levels can be achieved, the brightness is still far below that of fiber-lasers. Table 1 summarizes typical laser brightness numbers for different technologies.

Edge-emitter based approaches to high brightness are very complex, as multiple chips are required, each individually collimated and aligned.[3] In particular, edge-emitter technology is not amenable to 2D array fabrication to the level of precision required for direct alignment to a single 2D lens-array. Vertical-cavity surface-emitting

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Table 1. Performance comparison for different types of high-brightness laser technologies. The power conversion efficiency (PCE) is the optical power out to the electrical power in ratio and does not take into account power consumption from any colling apparatus. The brightness numbers were calculated using the formulas given in this work.

Description & reference	Power & beam performance	Brightness ($MW/cm^2.sr$)	PCE	Comments
Fiber-coupled diode pump module (976nm)[3]	100W from a 100μm/0.15NA fiber	21	35%	Uses 14 separate edge-emitters, individually collimated and free-spaced coupled, polarization combined.
Nd:YAG DPSS laser (946nm)[6]	10.78W, M^2=7.11	24	14% (est.)	End-pumped rod using a single 808nm module delivering 31.6W output power from a 400μm/0.22NA fiber.
CO_2 laser (10μm)[7]	5kW, diffraction limited	5,000	13%	Long wavelength. Fiber delivery not practical. Limited minimum achievable spot size.
Yb:YAG DPSS laser (1030nm)[9]	252W, $M_x^2 \sim 1.29$ $M_y^2 \sim 1.69$	6,720	9%	End-pumped slab using two stacks of 15 edge-emitter bars (940nm) delivering 1440W of total pump power.
Ytterbium fiber-laser (1075nm)[5]	2kW, diffraction limited	120,000	34% (est.)	Uses 144 fiber-coupled pump modules (976nm, 100μm/0.12NA fiber, 20W output power each).

lasers (VCSELs) on the other hand can easily be manufactured into single large 2D array chips, with a very large number of elements (10,000's) and delivering very high powers (>200W).[10] In addition, the position of the individual elements is photolithographically defined and therefore benefits from sub-micron accuracy, resulting in efficient coupling to a 2D micro-lens array.[11,12] Using such an approach, more than 40W of power at 976nm from a 400μm/0.46NA fiber was reported,[12] corresponding to a brightness of 48kW/cm^2.sr.

In this paper we present a study on high-brightness VCSEL technology and initial results for fiber-coupled modules based on a single 2D array VCSEL chip. We first review the concepts of brightness and etendue. In particular, we will see that the brightness of the VCSEL array is at best equal to the brightness of one element of the array, leading to a study of the brightness of single VCSEL devices. To increase the brightness of the single device, an external cavity configuration is described to improve the beam-quality. Finally, results on external cavity VCSEL arrays are presented. We achieved more than 30W from a 50μm/0.22NA fiber at 976nm, corresponding to a 10MW/cm^2.sr brightness, using a single chip. Scaling potentials will also be discussed.

2. REVIEW OF BRIGHTNESS AND ETENDUE

In this section, we will first review elements of brightness and etendue that are important for the rest of the discussion. The brightness of a source is given by[13]

$$B = P/E\,, \tag{1}$$

where P is the output power and E is the etendue given by

$$E = A\Omega\,, \tag{2}$$

where A is the spot area and Ω is the solid angle (units of Steradian, or sr).

We will consider two important cases that are the most generally encountered for lasers: a circular source and a rectangular source. In the case of the circular source, the solid angle is given by

$$\Omega = 2\pi\left[1-\cos\left(\frac{\theta}{2}\right)\right] \simeq \pi\left(\frac{\theta}{2}\right)^2 \simeq \pi(\text{N.A.})^2 \text{ for small angles}\,, \tag{3}$$

where θ is the (full) divergence angle, and N.A.= $\sin(\theta/2)$ is the numerical aperture. In the case of rectangular sources, the solid angle is given by

$$\Omega = 4\,\text{arcsin}\left[\sin\left(\frac{\theta_x}{2}\right)\sin\left(\frac{\theta_y}{2}\right)\right] \simeq \theta_x\theta_y \text{ for small angles}\,, \tag{4}$$

where θ_x and θ_y are the divergence angles in the x and y directions, respectively.

We can then write simplified expressions for the brightness of a low diverging laser source for the circular and rectangular cases

$$B \simeq \frac{P}{(\pi\omega_o\theta/2)^2} = \frac{P}{(M^2\lambda)^2} \text{ for a circular source}\,, \tag{5}$$

$$B \simeq \frac{P}{4(\omega_{ox}\theta_x)(\omega_{oy}\theta_y)} = \left(\frac{\pi}{4}\right)^2\frac{P}{M_x^2M_y^2\lambda^2} \text{ for a rectangular source}\,, \tag{6}$$

where we have used the expression for the Gaussian beam divergence given by $\theta = 2M^2\lambda/\pi\omega_o$, where M^2 is the beam quality parameter, ω_o is the beam-waist, and λ is the wavelength.[14] In particular, we note that the etendue of an ideal TEM_{00} mode is simply λ^2, so that the brightness of a diffraction-limited beam is P/λ^2.

Let us now consider a 2D VCSEL array of N identical elements. Theoretically, an ideal optical system exists that can reduce the etendue of the array to the sum of the etendues of the individual elements ($E_A = NE_e$). The total power of the array is the sum of the power of the individual elements ($P_A = NP_e$). Therefore, in the ideal case the brightness of the array can be made equal to the brightness of a single element. In practice however, several factors will reduce the array brightness compared to the ideal case. Such factors include non-uniform heating of the array (which will cause some devices in the array to perform worse than others) and imperfect optical systems (which will reduce the beam-quality) for example. In addition, there will be some coupling efficiency losses associated with the coupling of the array to a fiber or to a DPSS rod. Still, to find out if a certain brightness performance level is achievable (such as 100W from a 100μm/0.22NA fiber for example), it is useful to compare this desired performance level to the brightness of an individual device first, since a basic requirement is that the brightness of the single device be greater than the desired module brightness. The number of required elements can be estimated from the ratio of the required array power to the single device power. For a given device beam-quality and optical configuration, the maximum permissible number of devices in the array will scale as the etendue of the target (fiber, rod, ...).

3. BRIGHTNESS OF SINGLE VCSEL DEVICES

3.1 Analysis of brightness scaling

We developed a simple model to analyze the brightness behavior of VCSEL multimode devices, summarized hereafter. We start by making a few simplifying assumptions. First, we assume that the mode structure in the device is mainly dominated by thermal lensing. This can be true even for oxide-confined devices, when the index-induced confinement from the oxide aperture is weak and becomes less dominant than the thermal lensing effect, especially at higher operating currents. Second, we assume that the temperature profile inside the device is parabolic, thus generating a parabolic index profile. The lasing modes in the VCSEL can then be described as the Hermite-Gaussian modes, with a characteristic spot size ω_{oo} proportional to $D^{1/2}/\Delta T^{1/4}$, where D is the aperture diameter and ΔT is the temperature rise in the device (proportional to the index change in the structure).[14] Finally, we will assume the lasing modes' superposition to be equipartitioned, although this may not be exactly representative of practical cases.[15] In this case, it can be shown that the beam quality parameter M^2 scales as $(D/\omega_{oo})^2$ for multimode operation.[16] In this model, only the region of diameter D is pumped and generates gain. Modes that extend too much beyond the pumped region ($> D$) will experience severe losses and will not lase. As the temperature rise ΔT inside the device increases, the characteristic spot size ω_{oo} of the Hermite Gaussian distribution will decrease, thus allowing higher order modes to lase, thereby increasing M^2.

The temperature rise inside the device is directly related to the dissipated power: $\Delta T = Z_{th}P_{diss}$, where Z_{th} is the thermal impedance of the device, which is inversely proportional to the device diameter.[17] Finally, the dissipated power is directly related to the output power of the device: $P_{diss} = P(1 - \eta_e)/\eta_e$, where η_e is the power conversion efficiency (PCE) of the device.

From the above considerations and using Eq. 5, the brightness of a multimode VCSEL device of aperture D as a function of the injection current I is found to be

$$B(I) = \frac{K}{D}\frac{\eta_e(I)}{1 - \eta_e(I)}\,, \tag{7}$$

where K is a constant (W/cm.sr) that depends on the material properties.

Therefore, a multimode device will reach its maximum brightness B_m at the operating point of its maximum conversion efficiency $\eta_{e,m}$. For bottom-emitting devices ("P-down"), it was shown[12] that a device's maximum PCE remains fairly constant past $\sim 8\mu m$ aperture diameter and even in the limit of very large diameters, so that a multimode bottom-emitting device's maximum brightness is expected to scale as $1/D^{\dagger}$. For top-emitting devices, it was shown[19] that the maximum PCE remains fairly constant over a wide range of aperture diameters (roughly $8 \sim 40\mu m$), and then scales as $1/D$ in the limit of very large apertures. Therefore, the maximum brightness of a multimode p-up top-emitting device is expected to scale as $1/D$ over a range of medium to large aperture diameters, and then scale as $1/D^2$ in the limit of very large diameters.

Figure 1 shows the output power, power conversion efficiency, and brightness of a selectively oxidized, $30\mu m$ aperture diameter, top-emitting 808nm VCSEL device. Structural and processing details are given elsewhere.[19]

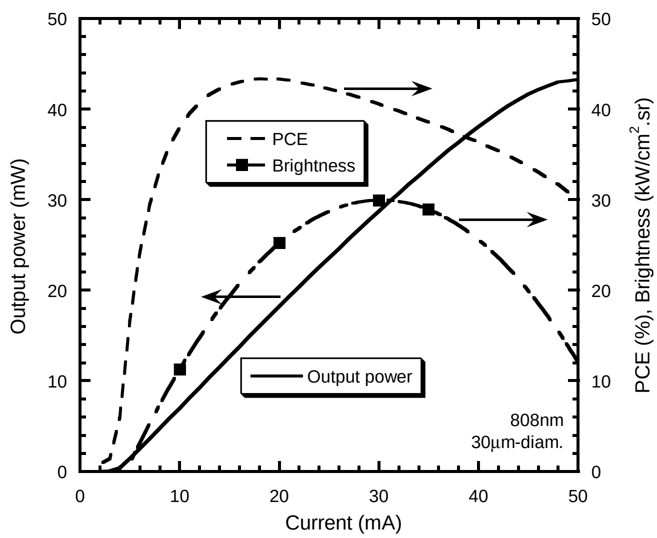

Figure 1. Output power, power conversion efficiency (PCE), and brightness (B) of a selectively oxidized, $30\mu m$ aperture diameter, top-emitting 808nm VCSEL device.

These devices were designed for high single-mode power from $4 \sim 5\mu$m diameter apertures and the index guiding strength from the oxide aperture is considered relatively weak. The brightness was determined by

†This assumes that the $1/D$ scaling law holds for the thermal impedance even in the limit of very large bottom-emitting devices. As suggested in Ref. 18 this may not be the case. Furthermore, thermal impedance numbers for large bottom-emitting devices will heavily depend on the device geometry, submount material, solder used, and the bonding quality and consistency. Our data and simulations suggest that in the case of very large ($> 150\mu m$ aperture diameter) p-down bottom-emitting 976nm VCSEL devices, the thermal impedance scales as $1/D^n$, where $1 < n \leq 2$, in which case the decrease in brightness with larger aperture diameters may not be so severe.

measuring the beam divergence of the device, at different currents. Although the device's maximum PCE and brightness points do not exactly coincide, they are close.

Figure 2 shows the maximum brightness versus aperture diameter for several top-emitting selectively oxidized 808nm devices. The single-mode data point corresponds to 4.7mW single-mode (TEM_{00}) output from a top-emitting 808nm VCSEL device.[19] For multimode devices, the brightness scales reasonably well with $1/D$, as predicted by our simple model.

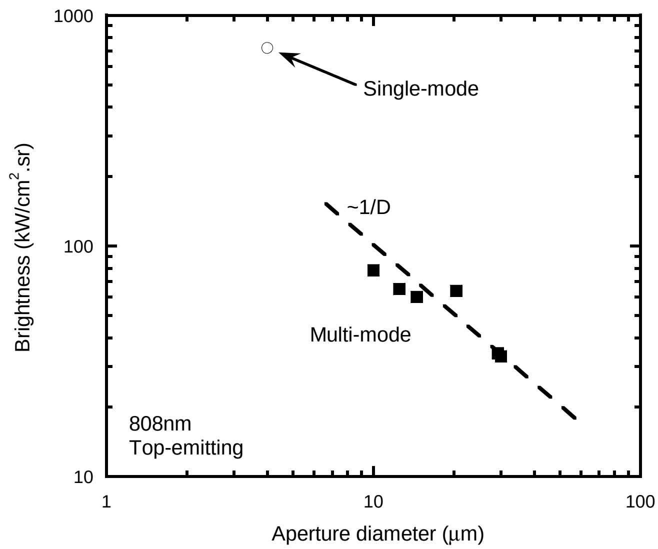

Figure 2. Maximum device brightness versus aperture diameter for top-emitting 808nm VCSEL devices.

Consequently, even though large bottom-emitting multi-mode single VCSEL devices can exhibit very high powers (> 3W),[20] their brightness remains low (few kW/cm^2.sr), far below that of low-power (only a few mW) single-mode devices ($\sim$700kW/cm^2.sr, Fig. 2).

3.2 High-brightness external-cavity VCSEL devices

It is clear that standard electrically pumped VCSEL devices do not have sufficient brightness to satisfy the requirements discussed in the Introduction (at least several MW/cm^2.sr for high brightness pumping applications). To increase the brightness of electrically pumped VCSELs, we would like to use large diameter high-power devices, but limit the number of higher order lasing modes. This can be achieved by operating the VCSEL in an external-cavity configuration.[21,22]

For such an approach, in order to achieve strong coupling to the external cavity, the middle mirror reflectivity is reduced, so that the VCSEL cannot lase without an external mirror. The external mirror consists of a flat piece of glass with a reflective coating on the external cavity side and an anti-reflection coating on the output side (Fig. 3).[22] Heating in the VCSEL provides sufficient thermal lensing so that the cavity is stable. Diffraction and spatial filtering in the external cavity are controlled by the VCSEL/external-mirror distance and provide high-order mode suppression. In lieu of a flat mirror, a curved mirror[21] or a GRIN lens[23] can also be used to increase the spatial filtering effect. A larger fundamental mode than could be achieved with a standard, small-aperture self-lasing single-mode VCSEL device can be generated and the ability to thus increase the size of the fundamental mode enables the generation of higher single mode powers. Using such an approach, up to 500mW of near-diffraction limited TEM_{00} power ($M^2 \sim 1.2$) has been reported from a large ($\sim 150\mu$m-diameter) 976nm VCSEL device,[24] corresponding to a brightness of 36.5MW/cm^2.sr.

We designed and fabricated 976nm bottom-emitting ("P-down") VCSEL structures optimized for external cavity operation. Epitaxial structure and device processing is similar to work described elsewhere.[12] The main differences are that the reflectivity of the output N-DBR is reduced and the doping of the N-GaAs substrate is

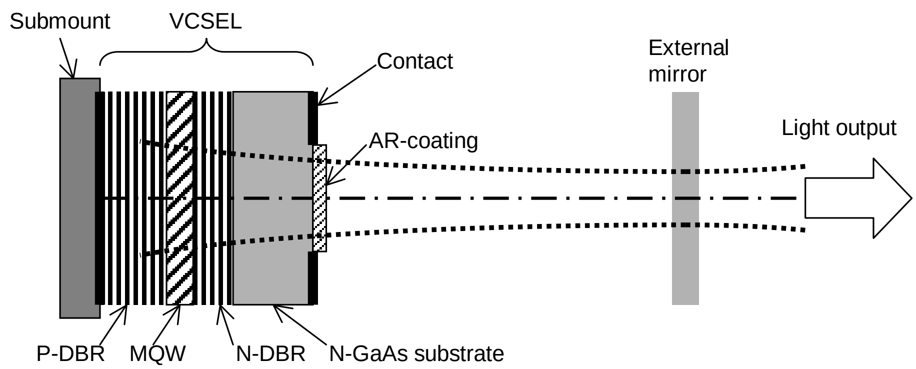

Figure 3. Schematic showing the external-cavity VCSEL arrangement for high-brightness operation. The active region consists of multiple quantum-wells (MQW) and the N-DBR is partially reflecting in order to achieve strong coupling to the external cavity.

lowered to minimize losses in the external cavity. The devices are packaged on diamond submount and copper carrier for efficient heat removal.

Figure 4 shows the performance of a 73μm-diameter external cavity device operating in the TEM_{00} mode. A maximum single-mode output power of 216mW is reached at 400mA, with $M^2 \sim 1.2$, corresponding to a brightness of 15.7MW/cm^2.sr. At 400mA, the flat external mirror is positioned approximately 2mm from the VCSEL chip. Any further increase in current results in either degraded beam quality or lower output power, regardless of the mirror position. The maximum single-mode power conversion efficiency for this device is 22%, at an output power of 150mW.

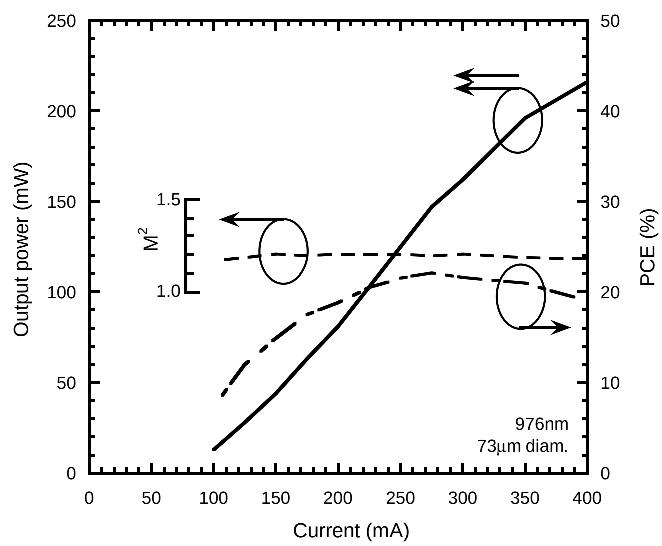

Figure 4. Single-mode CW performance of a 73μm diameter external cavity VCSEL device. The device operates in a TEM_{00} mode, with $M^2 \sim 1.2$.

We recently fabricated larger 976nm VCSEL devices for external cavity operation and obtained more than 1W of TEM_{00} from a 300μm diameter device, with $M^2 \sim 1.1$, corresponding to a brightness of 86.8MW/cm^2.sr.

4. EXTERNAL CAVITY VCSEL ARRAYS

We have fabricated 2D VCSEL arrays of high-brightness external cavity devices. Processing and packaging is similar to work described elsewhere for high power VCSEL arrays.[12] The external cavity set-up for arrays is shown in Figure 5. In such a set-up, a large flat external mirror is aligned to the array such that each element lases in a single TEM_{00} mode. An AR-coated micro-lens array is then used to collimate the individual beams, effectively filling the total emitted area from the array. A simple focusing lens is then used to couple the light into the fiber or other target (such as a DPSS rod for example). Another possible arrangement would be to replace the flat-mirror/micro-lens-array pair with a unique reflecting micro-lens array, acting as an array of curved mirrors for each individual elements. Figure 6 shows the performance of a 5mm $\times$ 5mm external cavity array coupled to a 100μm/0.22NA fiber. The array contains a few hundred 73μm-diameter devices. The array is mounted on a diamond submount and assembled on a micro-channel cooler.

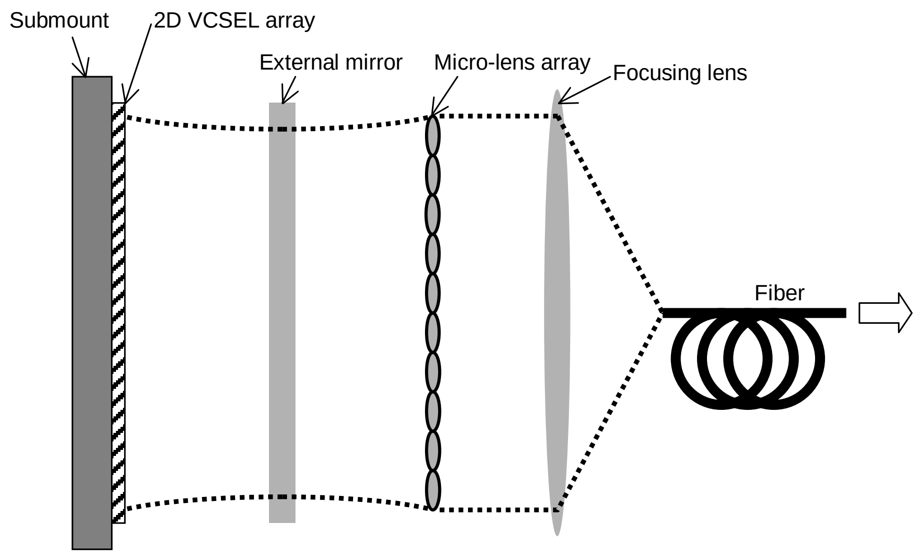

Figure 5. Schematic showing the external-cavity VCSEL array arrangement for high-brightness operation. The large flat external mirror is aligned to the array such that each element lases in a single TEM_{00} mode. An AR-coated micro-lens array is then used to collimate the individual beams, effectively filling the total emitted area from the array. The AR-coated focusing lens couples the light into the fiber.

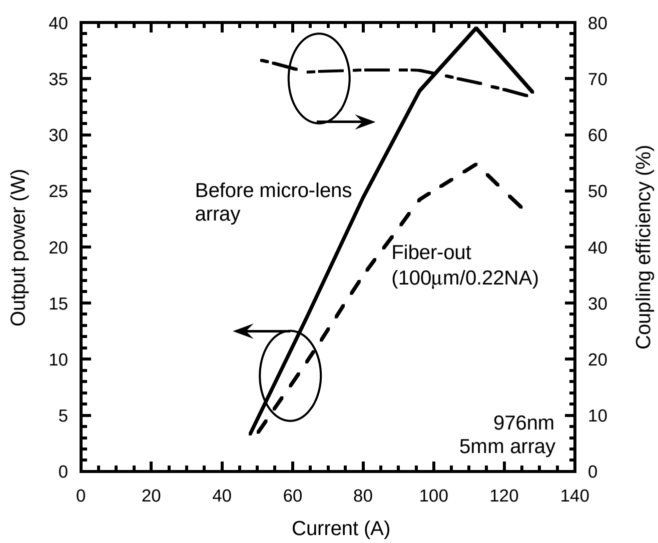

Figure 6. Performance characteristics of a 976nm external cavity 2D VCSEL array designed for coupling into a 100μm/0.22NA fiber. The output power is measured before the micro-lens array (after the flat external mirror) and at the fiber output.

For this array, the power measured before the micro-lens array (after the flat external mirror) reaches a maximum of 39.5W. The maximum fiber-out power is 27.4W, corresponding to a brightness of 2.3MW/cm^2.sr. The coupling efficiency remains fairly constant (∼70%) throughout the operating range. The maximum fiber-out PCE is ∼11%, at an output power of 24.2W. The emission spectrum is similar to that of standard high-power 2D VCSEL arrays (<1nm),[12] which is expecially advantageous for pumping applications where the absorption spectrum of the pumped medium is narrow.

We recently fabricated smaller arrays (4mm×4mm), with a smaller number of elements (∼100), but with larger elements (∼110μm diameter). Such elements typically produce 400∼500mW of single-mode power, with excellent beam quality ($M^2 \sim 1.1$). These arrays were designed for coupling into a 50μm/0.22NA fiber. Using a single array chip, we obtained more than 30W power fiber-out, and a maximum fiber-out PCE of 14%. This performance corresponds to a 10MW/cm^2.sr brightness. We believe the improvement in brightness is mainly due to the lower heat-load and the improved beam-quality of the elements. As a comparison, to achieve a similar output power and brightness, an edge-emitter based approach could require seven separate chips, each individually collimated and aligned to the fiber.[3]

To scale up the power and the brightness of VCSEL-based modules, higher-power single-mode VCSEL devices can be used. But this generally means using larger aperture devices, resulting in much larger array chips and higher heat-loads. Therefore, while we have demonstrated 1W, ∼300μm-diameter single-mode external-cavity VCSEL devices, work needs to be done to improve the PCE of these devices so that they can be efficiently used in an array configuration. Another approach would be to use polarization combining of two array chips to double the power and brightness. Such an approach can be readily implemented in the external-cavity VCSEL array architecture by inserting Brewster plate elements for example. Finally, the narrow emission spectrum (<1nm) and good wavelength stability (∼0.07nm/K) of these arrays naturally lends itself to efficient and relatively dense spectral beam combining. These techniques along with improvements in PCE should allow scaling of the power and brightness of VCSEL-based modules to very high levels.

5. CONCLUSIONS

Using a single 2D VCSEL array chip in an external cavity configuration, we have demonstrated more than 30W output at 976nm from a 50μm/0.22NA fiber, corresponding to a brightness of 10MW/cm^2.sr. This represents a significant reduction in module complexity and cost compared to edge-emitter-based approaches, which require several separate edge-emitter devices and complex optics. Furthermore, the VCSEL-based approach lends itself to spectral combining (because of the narrow <1nm spectral width) and polarization combining to scale up the power and brightness. However, more work is required to improve the efficiency of VCSEL-based high-brightness modules (currently ∼14%).

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