Oxide-Confined Vertical-Cavity Surface-Emitting Lasers Pumped Nd:YVO_4 Microchip Lasers

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***Abstract*—In this letter, we demonstrate an experimental study of using a large area oxide-confined vertical-cavity surface-emitting laser (VCSEL) to pump a Nd:YVO_4 microchip laser. The maximum output power of 1.2 mW in TEM_{00} mode is obtained with a pump power of 8.2 mW. Experimental results show that the complex transverse modal behavior of VCSELs in the higher injection current may cause an impediment of power scaling.**

***Index Terms*—Oxide-confined, solid state lasers, transverse mode, vertical-cavity lasers.**

DIODE-PUMPED solid-state lasers have been shown to be efficient, compact, and reliable all-solid-state optical source. Numerous approaches in realization of various optical configurations of diode-pumped solid-state lasers have been introduced [1]. An edge-emitting diode laser is usually used as a pump source in a typical diode-pumped solid-state laser. Recently, vertical-cavity surface-emitting lasers (VCSELs) have been proposed to be an alternative pump source [2]. The advantages of VCSELs over edge-emitting lasers are longitudinal single-mode emission, lower threshold currents, simply array integration, and smaller wavelength drift with ambient temperature changes. Furthermore, the circular symmetric cavity exhibits round and astigmatism-free beams, which is beneficial in beam-focusing applications. The modal behavior of the VCSELs strongly depends on the confinement mechanism. The first available devices were air-post VCSELs with index-guiding by a step-like index profile of etched mesas. Compared with the air-post VCSELs, proton implanted VCSELs represented for quit a long time the state-of-the-art device because of their lower threshold currents and higher efficiencies. Using gain-guided VCSELs to pump microchip laser has been previously demonstrated; the operation region is just above lasing threshold because of limitations of available pump power [3].

In recent years, VCSELs have made substantial progress with the advent of oxide-confined structures that promise a further reduction of the threshold current by a more efficient current confinement and low-loss optical confinement [4]. In this work, we present the first experimental investigations of using oxide confined VCSELs to pump a microchip laser. The maximum output power of 1.2 mW in TEM_{00} mode is obtained with a pump power of 8.2 mW. Experimental results show that the limitations of power scaling arise mainly from the complex transverse modal behavior of VCSELs in the higher injection current.

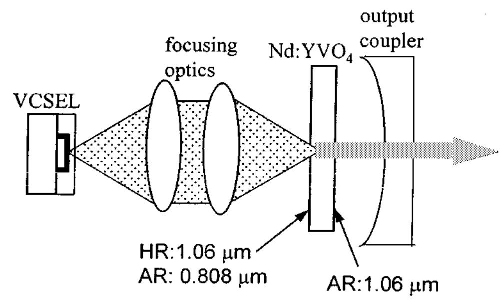

Fig. 1. Schematic of oxide confined VCSEL pumped Nd:YVO_4 microchip laser.

The experimental setup for the oxide confined VCSEL pumped microchip laser is shown in Fig. 1. The laser crystal is 1 mm long and doped with 2.0% Nd^{3+} concentration. The absorption coefficient of the present Nd:YVO_4 crystal is about 20, 40, and 20 cm^{-1} at the pump wavelength of 806, 808.5, and 812 nm. The saturation intensity of the laser crystal is about 2.42 kW/cm^2. One side of the Nd:YVO_4 crystal was coated so as to be highly reflecting at the lasing wavelength $(R > 99.8\%)$ and highly transmitting at the pump wavelength $(T > 95\%)$. The other side was antireflection coated at the lasing wavelength $(R < 0.2\%)$. The output coupler is a concave mirror with the radius of curvature 10 mm and the reflectance of $R = 99.2\%$. The total length in the present resonator is ~5.0 mm.

The pump lasers, grown with metal–organic chemical vapor deposition (MOCVD) to emit at a wavelength within 809 ± 3 nm, consist of a multiquantum-well active region and doped semiconductor distributed Bragg reflector (DBR) mirrors to form the vertical cavity. The active region comprises three $Al_{0.08}Ga_{0.92}As$–$Al_{0.36}Ga_{0.64}As$ quantum wells with well and barrier thickness of 100 and 100 Å, respectively. The spacers at both sides of quantum well were added to form a $1 - \lambda$ cavity. A high-Al composition $Al_{0.97}Ga_{0.03}As$ layer is placed at the first P-DBR mirror that is oxidized for current and optical confinement. The device processing was carried out as follows. The wafers were wet oxidized at 425 °C and the oxidation time is controlled to fabricate a 40-μm oxide aperture in a 110-μm mesa structure. Then a SiN passivation layer is deposited followed by Ti–AuBe–Au p-metal evaporation. AuGe–Au N-metal was finally evaporated and annealed after thinning substrate to 200 μm. Fig. 2 shows

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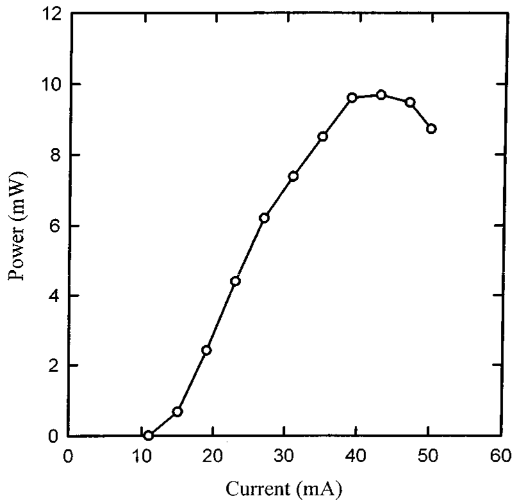

Fig. 2. I–L characteristic of the present oxide confined VCSEL.

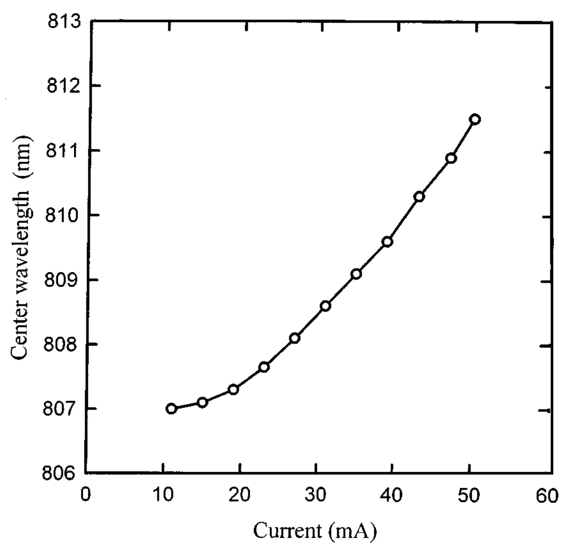

Fig. 3. Emission center wavelength of the present VCSEL as a function of injection current.

the output characteristic of the present VCSEL. The threshold current is 10.5 mA and the maximum output power without temperature control is 9.8 mW. The center wavelength of the present VCSEL changes with driven current at around 0.11 nm/mA, as can be seen from Fig. 3. The dominant mechanism in causing the redshift of the VCSEL emission is Joule heating at the heterojunction interfaces of the DBR stacks and near the active region because of nonradiative recombination. Even so, the wavelength emission before rollover is still within the absorption bandwidth (806–812 nm) of the Nd:YVO_4 crystal.

The coupling optics is used to reimage the pump beam into the laser crystal. Both lenses and objectives in Fig. 1 have $\mathrm{NA} = 0.45$. For the present cavity, the mode size on the microchip is given by [1]

$$\omega_o^2 = \frac{\lambda_l}{\pi}\sqrt{L(R-L)} \tag{1}$$

where λ_l is the lasing wavelength, R is the radius of curvature of the output coupler and L is the cavity length. For $\lambda_l = 1.064$ μm, $R = 10$ mm, and $L = 5$ mm, the cavity mode size is around 41 μm. Note that the pump-to-mode size ratio should be designed to be less than unity for operating in the TEM_{00} mode [5]. Fig. 4 shows the input–output characteristics for the present VCSEL pumped Nd:YVO_4 laser operating in the TEM_{00} mode. It can be seen that the threshold pump power is around 1.8 mW; the maximum output power at 1064 nm is about 1.2 mW; and the slope efficiency is 17.6%. The slope efficiency is lower than the typical result obtained with an edge-emitting laser diode because the high value of reflectivity on the output coupler is used to have a low threshold [6]. Even so, to our knowledge, the present result is the highest output power achieved to date with a VCSEL to pump a Nd:YVO_4 laser. The drop of output power for the pump power higher than 8.2 mW is due to a strongly increased NA of the VCSEL not due to a decrease of pump power absorption at long wavelengths. Impediment of power scaling is found to be due to the transverse-mode change of oxide confined VCSEL in the high injection current. Transverse mode patterns of the present VCSEL are presented in Fig. 5 for injection currents of 16 mA (a), 22 mA (b), 30 mA (c), and 39 mA (d). At injection current of 16 mA, which corresponds to a low pump rate, the transverse pattern contains both a low order mode $(\mathrm{TEM}_{1,0})$ and a high-order Laguerre Gaussian (LG) mode $(\mathrm{TEM}_{14,0})$ with a divergence of about 15°. Here the divergence is defined as the full angle at half the maximum intensity. With increased injection current from 22 to 39 mA, higher order LG modes appear in the transverse mode patterns and the divergence angle increases from 23, via 32 up to about 50° at the currents defined. The previous studies show that the tendency to higher order mode emission in the higher injection current is mainly caused by the influence of pump induced current spreading in the confinement region and secondarily by the effects of spatial hole burning and thermal gradients in the cavity [7], [8].

A strongly increased NA of the VCSEL leads to a larger average pump size and causes a reduction of the overlap efficiency. The overlap efficiency is proportional to the factor of

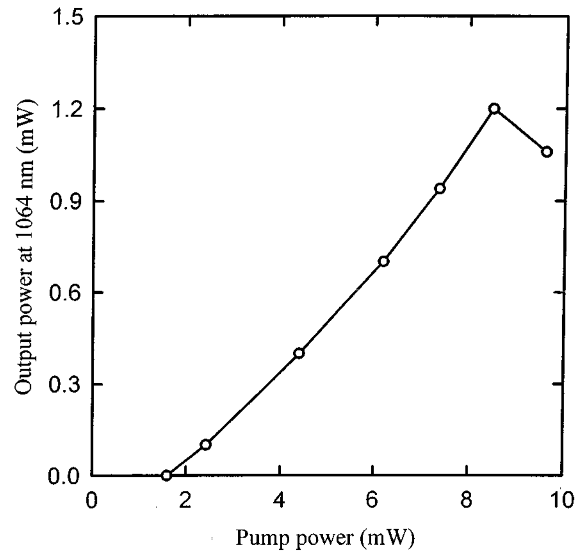

Fig. 4. The input–output characteristics for the present VCSEL pumped Nd:YVO_4 laser operating in the TEM_{00} mode.

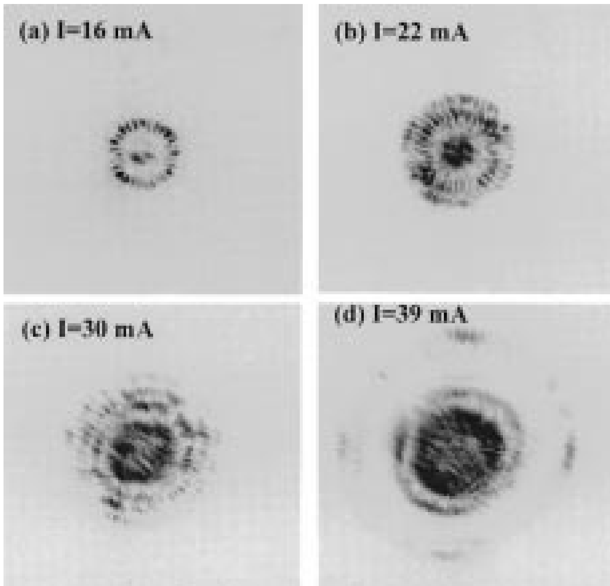

Fig. 5. Transverse mode patterns of the present VCSEL for injection currents of (a) 16 mA , (b) 22 mA, (c) 30 mA, and (d) 39 mA.

$\omega_o^2/\left(\omega_o^2+\omega_p^2\right)$, where ω_p is the average pump size [1]. It can be found that when ω_p is slightly less than ω_o the overlap efficiency can be close to unity. As ω_p is greater than ω_o, however, the overlap efficiency may dramatically decrease. This is the reason why the output power can be almost linear up to a pump power of 8.2 mW, despite the changing pump mode. The rollover in pump power above 9 mW is related to the mismatch of pump-to-mode size ratio. In general, the complex transverse modal behavior of VCSELs in the higher injection current is a major drawback for many practical applications. Recently, several techniques have been proposed to select low order transverse modes in a large area oxide-confined VCSEL [9]. We believe that the transverse mode control in a large area VCSEL is the key issue to further scale up output power in a microchip laser.

We have demonstrated an oxide-confined VCSEL pumped microchip laser with a slope efficiency of 17.6% and an output power greater than 1 mW in the TEM_{00} mode operation. From the experimental results it can be concluded that even though there is substantial scope for further power scaling, the transverse mode control in a large area VCSEL becomes important because of the coupling efficiency.

REFERENCES

[1] W. Koechner, *Solid-State Laser Engineering*. New York: Springer-Verlag, 1999, pp. 289–392.

[2] H. D. Summers, J. M. Preston, A. J. Kemp, B. D. Sinclair, and J. S. Roberts, “Microchip laser with vertical-cavity surface-emitting laser diode pump,” presented at the CLEO 1999, Baltimore, MD, Paper CFD4.

[3] J. Wu, G. Iordache, H. D. Summers, and J. S. Roberts, “Optical characteristics of VCSEL pumped microchip lasers,” *Opt. Commun.*, vol. 196, pp. 251–256, 2001.

[4] D. L. Huffaker, D. G. Deppe, K. Kumar, and T. J. Rogers, “Native-oxide defined ring contact for low-threshold vertical-cavity lasers,” *Appl. Phys. Lett.*, vol. 65, pp. 97–99, 1994.

[5] T. Y. Fan and A. Sanchez, “Pump source requirements for end-pumped lasers,” *IEEE J. Quantum Electron.*, vol. 26, pp. 311–316, Feb. 1990.

[6] P. Laporta and M. Brussard, “Design criteria for mode size optimization in diode-pumped solid-state lasers,” *IEEE J. Quantum Electron.*, vol. 27, pp. 2319–2326, Oct. 1991.

[7] C. Degen, I. Fischer, and W. Elsãßer, “Transverse modes in oxide confined VCSELs: Influence of pump profile, spatial hole burning, and thermal effects,” *Opt. Express*, vol. 5, pp. 38–47, 1999.

[8] W. Nakwaski and R. P. Sarzala, “Transverse modes in gain-guided vertical-cavity surface-emitting lasers,” *Opt. Commun.*, vol. 148, pp. 63–69, 1998.

[9] H. Martinsson, J. A. Vukušíc, M. Grabherr, R. Michalzik, R. Jäger, K. J. Ebeling, and A. Larsson, “Transverse mode selection in large-area oxide-confined vertical-cavity surface-emitting lasers using a shallow surface relief,” *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1536–1538, Dec. 1999.