Two-dimensional Er:YSGG microlaser array pumped with a monolithic two-dimensional laser diode array

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We have demonstrated one- and two-dimensional Er:YSGG microlaser arrays at 2.8-μm output wavelength with power levels up to 900 mW cw. The one-dimensional microlaser arrays are based on conventional edge-emitting laser diodes, and the two-dimensional microlaser arrays are based on surface-emitting monolithic two-dimensional laser diode arrays with 45-deg deflectors.

Diode-laser-pumped solid-state microlasers with short monolithic resonators permit the fabrication of compact and simple solid-state lasers. These compact solid-state lasers, also referred to as microchip lasers, comprise a thin solid-state gain medium polished flat on both sides and reflectors coated or otherwise attached to the input and output surfaces of the gain medium.[1] Several different microlasers have been demonstrated that use Nd:YAG or other solid-state materials. The microlaser array architecture can easily be extended to arrays of microlasers. One-dimensional (1-D) arrays of microlasers with linear laser diode bars have been demonstrated,[2,3] and high-power two-dimensional (2-D) operation based on five-stack laser diode bars has been demonstrated.[4] Although the output from these microlaser arrays is not diffraction limited, the brightness remains very high and may be suitable for material-processing and medical applications, among others. The configuration of the 2-D microlaser array is uniquely suited for combination with recently developed monolithic 2-D arrays of surface-emitting laser diodes.[5–10] In this Letter we demonstrate what is to our knowledge the first operation of a microlaser array based on a high-power monolithic 2-D laser diode array. The experiments are based on an Er:YSGG microlaser that is pumped near 965–975 nm and has a laser transition at 2.8 μm. Comparison of Er^{3+} in different hosts has shown that the YSGG host is more efficient than others such as YAG.[11]

A schematic diagram of the 1-D microlaser array is shown as Fig. 1. The output power from a laser diode bar is coupled to a Er:YSGG microlaser by optional micro-optics. The 1-cm-long laser diode bar comprises 12 emitters with 200-μm width on 800-μm centers (SDL 3450-S). The bar has a threshold pump current of 4 A and a slope efficiency of 0.78 W/A and operates at up to 20-W cw output power. The spectrum of the bar emission is centered around 973 nm with a width of 2 nm FWHM. The optional micro-optics comprises a 500-μm-radius semicylinder lens (Schott SF11-6) with a 1-mm focal length for collimation of the light perpendicular to the laser diode junction and a microlens array with 600-μm-diameter lenses on 800-μm pitch and 1000-μm focal length. The 30% doped Er:YSGG microchip lasers were fabricated with a thickness of 1 mm and dielectric reflectors deposited directly upon the facets. The input reflector has 95% transmission at the 973-nm pump wavelength and >99.9% reflection at the 2.8-μm lasing wavelength. The reflectivity of the output facet is 99.6% at 2.8 μm. Also, the output reflector reflects 99% of the pump wavelength for more efficient absorption of the pump beam.

Figure 2 shows the output power at 2.8 μm as a function of incident pump power from the laser diode array for three different optical coupling configurations between the laser diode array and the microlaser array. In the first experiment, the laser diode array is butt coupled to the microlaser array, resulting in a maximum output power of 500 mW at 2.8-μm wavelength. When a single cylinder lens or a cylinder lens followed by a microlens array is used, the maximum output power at 14-W pump power is 700 or 900 mW, respectively. The higher output power obtained with the microlenses is a result of the smaller pump spot size, which reduces the pump threshold power for oscillation. Without the micro-optics the pump spot size in the microlaser is contained within a 50-μm by 250-μm aperture at the input reflector of the microlaser and freely diverges in the microlaser with a spot size of 600 μm by 350 μm at the output reflector. With a cylinder and microlens array the light from the laser diode emitters is contained within a 300-μm-diameter aperture over the full double-pass length of the microlaser. Additional results of laser diode beam shaping along with detailed calculations are presented elsewhere.[3,12]

To scale the microlaser array to two dimensions, we fabricated 2-D monolithic pump arrays at 970-nm wavelength. Figure 3(a) is a schematic diagram of the layout of the 2-D monolithic laser diode array. The 2-D array has 48 broad-area lasers with

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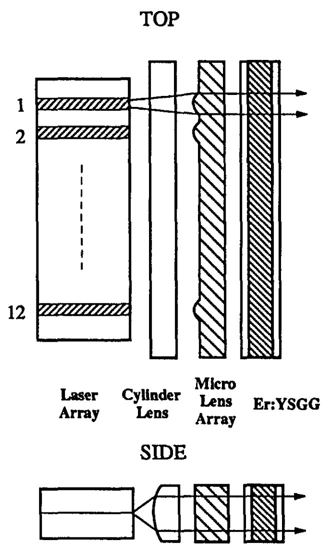


Fig. 1. Schematic diagram of the experimental setup of the 1-D Er:YSGG microlaser array pumped with a 1-D edge-emitting conventional laser diode bar.

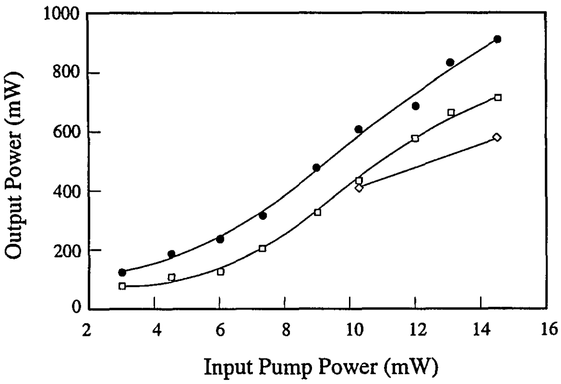
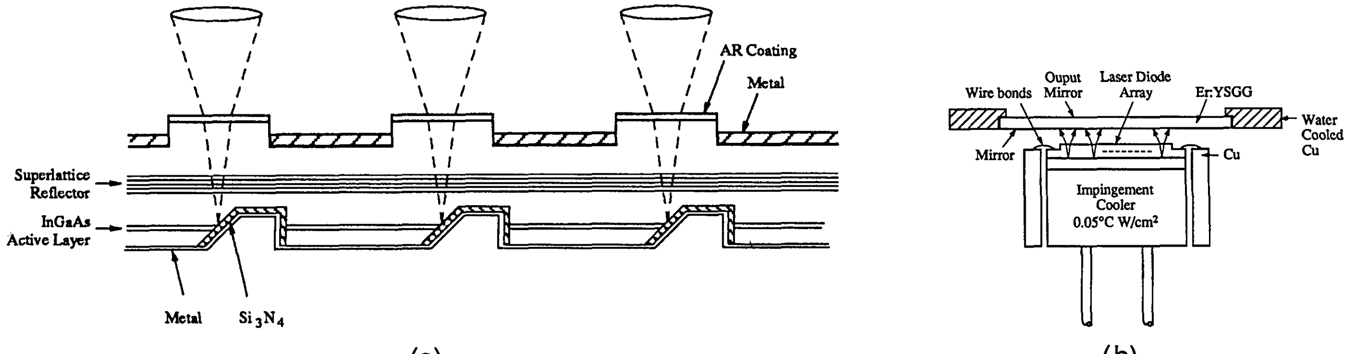


Fig. 2. Measured output power from the 1-D Er:YSGG microlaser as a function of the incident pump power from a 12-element laser diode bar for three different optical coupling schemes between the laser diode and the Er:YSGG microlaser. Filled circles, cylinder lens and microlens array; open squares, cylinder lens only; open diamonds, no optics, direct butt-coupling.

a width of 200 μm and a 1-mm cavity length. The spacing between the lasers in the direction perpendicular or parallel to the waveguide is 750 or 150 μm, respectively. The individual laser cavities of the 2-D laser diode array, shown in Fig. 3(a), are formed by ion milling of 90- and 45-deg mirrors.[10] After ion milling, the 90-deg mirror is coated with an 85% reflector. The light from the waveguide is deflected upward through the GaAs substrate from the 45-deg mirror and is partially reflected from an epitaxially grown superlattice reflector above the 45-deg mirror, which reflects approximately 5% of the light. The light from the laser diodes is coupled out through the antireflection-coated GaAs substrate. The laser array is bonded junction side down on an efficient water-cooled heat sink. The thermal resistance of the bonded device is 0.1 °C/W cm^2. Characterization of the laser diode array under quasi-cw, 100-μs, 50-Hz operation demonstrates 132-W peak output power at 250-A pump current. The threshold current for the laser diode array is 22 A, and the differential efficiency is 0.6 W/A. These power levels, thresholds, and efficiencies compare well with the results obtained with conventional cleaved laser diode bars discussed above. The measured spectrum from the array is centered at 973 nm with a FWHM of 7.5 nm. Figure 3(b) is a schematic diagram of the 2-D laser diode array butt coupled to an Er:YSGG microlaser that is identical to the microlaser used in the 1-D laser experiments. As the 100-μs long pulses are considerably shorter than the 1.3-ms lifetime of the upper state, we experimented with varying the pump pulse length. The best microlaser efficiency was obtained at 4-ms pump pulse length. The pump laser was therefore operated with 4-ms pulses at a 5-Hz repetition rate. The maximum peak power from the array at the 4-ms pulse length is 42 W, limited by the 100-A current available from the power supplies (SDL 830's).

Figure 4 shows the measured output power at 2.8 μm versus the incident pump power from the 48-element 2-D laser array. The threshold pump power is 20 W, and the maximum output power at 2.8-μm wavelength is 630 mW at 42-W input pump power. Based on our measurement of the laser diode array, which shows a maximum output power of 130 W, several-watt output power at 2.8 μm is predicted with the laser diode array operating at its maximum output power. Comparison between the 2-D results and the 1-D results shows a lower output power and efficiency for the 2-D array. The main reason for the lower efficiency of the 2-D array is



(a) (b)

Fig. 3. (a) Schematic diagram of the surface-emitting laser array and (b) experimental setup of the 2-D Er:YSGG microlaser array pumped with a 2-D surface-emitting laser diode array.

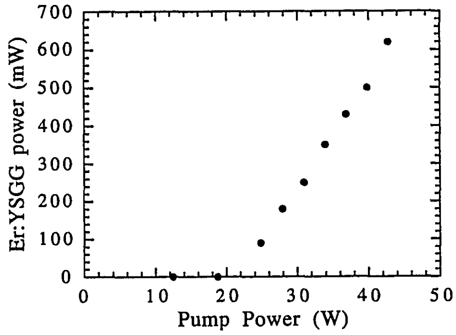


Fig. 4. Measured output power from the 48-element 2-D microlaser array pumped with a monolithic 2-D laser diode array as a function of the input pump power with quasi-cw, 4-ms, 5-Hz operation.

probably the wider pump spectrum of the 2-D pump array. We investigated the effect of microlaser efficiency as a function of pump spectrum by varying the pump wavelength of the laser diode in the 1-D microlaser array by changing the temperature of the laser diode heat sink from 12.5 to 25 °C. At 976-nm peak wavelength from the laser diode array the microlaser output power is reduced by 40% compared with the output power from the microlaser array pumped at 973 nm. A similar reduction in efficiency is found at wavelengths shorter than 973 nm. These experiments confirm that the lower efficiency of the 2-D microlaser array with a pump spectrum extending from 969 to 977 nm FWHM is to a large extent related to the relatively wide pump spectrum of the 2-D array. Measurements of the pump spectrum as a function of the position in the near field of the 2-D laser diode arrays shows that the broad spectrum of the 2-D array is related to a broader spectrum of each of the individual lasers and is not related to a variation in wavelength over the 2-D pump array elements. In addition to improving the efficiency of the 2-D microlaser array by pumping with a narrower spectrum, one can further improve the total efficiency and output power of the microlaser with beam-shaping micro-optics between the laser diode array and the microlaser array, as demonstrated in the 1-D microlaser array experiments.

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