Continuous-wave and passively Q-switched cladding-pumped planar waveguide lasers

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Greater than 12 W of average output power has been generated from a diode-pumped Yb:YAG cladding-pumped planar waveguide laser. The laser radiation developed is linearly polarized and diffraction limited in the guiding dimension. A slope efficiency of 0.5 W/W with a peak optical–optical conversion efficiency of 0.31 W/W is achieved. In a related structure, greater than 8 W of Q-switched average output power has been generated from a Nd:YAG cladding-pumped planar waveguide laser by incorporation of a Cr^{4+}:YAG passive Q switch monolithically into the waveguide structure. Pulse widths of 3 ns and pulse-repetition frequencies as high as 80 kHz have been demonstrated. A slope efficiency of 0.28 W/W with a peak optical–optical conversion efficiency of 0.21 W/W is achieved.

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Cladding-pumped planar waveguide lasers[1] (CPPWLs) are the two-dimensional analogs of one-dimensional double-clad fiber lasers. These five-layer structures were developed several years ago at Maxios Laser Corporation as an outcome of recent developments in thermal bonding technology[2] and have recently begun to appear in the scientific literature.[3] The CPPWL reported here consists of five layers with either a Nd:YAG or a Yb:YAG core layer. The CPPWL structure is shown in Fig. 1. Using separate confinement structures for the laser radiation developed and the pump radiation delivered enables this class of laser to generate high gains and to be efficiently pumped by use of ordinary laser diode bars. In particular, no radiance conditioning or other optical components are required for the diode light to be efficiently delivered into the waveguide structure (WS).

Recently we demonstrated a cw Yb:YAG CPPWL that serves to demonstrate the average power capability and efficiency of this approach. In the cw Yb:YAG laser the active core consists of an 8-μm-thick layer of 10 atm.% Yb:YAG. This core is clad on each side by a 5-μm-thick undoped YAG layer. The individual layers are joined by diffusion bonding.[4] Owing to the polarizability of the Yb in the central core layer, the refractive index of the core is slightly larger than the refractive index of the undoped YAG cladding layers, by $\sim 1.4 \times 10^{-3}$. The weak waveguiding provided by this index step, combined with the gain guiding provided by the core layer, is sufficient to ensure single-transverse-mode operation in the guided dimension up to the 40 W of delivered pump power investigated here. The outermost cladding layers used in the WS are sapphire. The top sapphire layer is 300 μm thick, and the bottom layer is 2 mm thick and in contact with a water-cooled copper heat sink. The refractive index of sapphire at 1.76 serves to confine the pump light from the two proximity-located laser diode bars, which are positioned within ~ 10 μm of the sides of the structure. The cw diode bars used here are 1 cm long, emit at the 940 nm peak of the Yb:YAG absorption, and were procured from the Coherent Semiconductor Group.[5] The overall footprint of the WS is 1 cm long by 0.5 cm wide. The high reflector (HR) and the output coupler (OC) optical coatings are monolithically applied to the WS. The OC has a reflectivity of 0.7 at 1030 nm, and both the HR's and the OC's ends are flat. Figure 2 displays the measured optical performance of this system. The slope efficiency achieved in cw operation is 0.5 W/W, and the peak optical–optical efficiency is 0.31 W/W at the peak optical output power of 12.4 W. In the guided dimension, the laser beam quality is measured to be nearly diffraction limited at all pumping powers, with an M^2 value of 1.07. In the unguided dimension, the beam is observed to be highly multimode, as would be expected for the flat–flat resonator

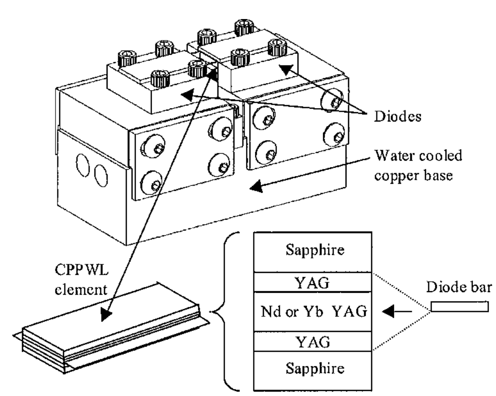

Fig. 1. Schematic drawing of our CPPWL system. The laser is pumped by two laser diode bars located within ~ 10 μm of either side of the WS. All components are mounted upon a copper base plate that is water cooled.

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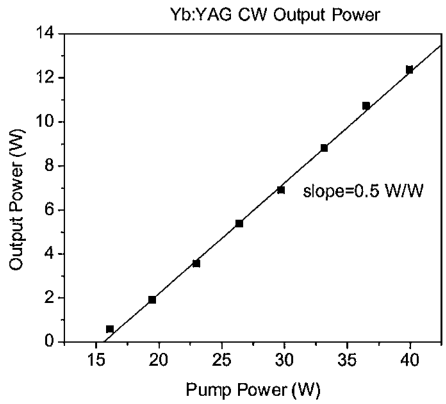

Fig. 2. cw output power from a Yb:YAG CPPWL as a function of the delivered pump power. The pump power is corrected for the Fresnel losses that are incurred at the uncoated sides of the WS and so corresponds to the pump power actually delivered into the structure.

used. Under all pumping conditions, the output from the system is TE polarized with greater than 90% purity.

The Nd:YAG CPPWL used in our Q-switching investigations is similar in design to the Yb:YAG described above, except that the central core layer is 20 μm thick and consists of 1 atm. % of Nd:YAG. All other layer thickness are identical of those of the Yb:YAG WS described above. Into this WS we have incorporated a Cr^{4+}:YAG passive Q switch[6] in the center of the structure by replacing a section of the 20-μm thick Nd:YAG layer, extending across the 5-mm width, with a section of Cr^{4+}:YAG that in the direction of the laser cavity is 540 μm long. The Cr^{4+}:YAG used has a measured absorption coefficient of 4.34/cm at 1064 nm. The resonator design for this Nd:YAG passively Q-switched CPPWL is similar to that used for the Yb:YAG system above; it uses a flat mirror surface at each end of the WS with a 50% reflective OC coating, and an HR coating applied monolithically. Two Coherent cw diode bars emitting at 808 nm serve as the pump source. Figure 3 displays both the output power and the pulse-repetition frequency (PRF) for this system as a function of the optical pump power delivered into the WS. The slope efficiency of this laser is 0.28 W/W, and, at the maximum delivered pump power of 39 W, the average output power of the laser is 8.1 W, leading to a peak optical–optical efficiency of 0.21 W/W. The PRF of the Q-switched output pulses was observed to increase linearly with delivered pump power at low pump powers and then eventually to roll over at higher pump powers, as displayed in Fig. 3, achieving a maximum value of ~80 kHz. In addition to suffering roll over, the PRF was observed to become progressively more unstable as the pump power increased. This is indicated by the error bars in Fig. 3, which represent the standard deviation of the multiple PRF measurements that were made for each data point. The instability in the PRF is not completely understood but may be attributed partially to the 4.1-μs excited-state lifetime of the Cr^{4+}:YAG (Ref. 7); at 80 kHz the time between extraction pulses is only 12.5 μs. Additionally, the large number of transverse modes supported in the unguided dimension of our flat–flat cavity, along with their varying loss, may contribute to jitter in their buildup time and so contribute to the observed PRF instability. The Q-switched pulse width was observed to fluctuate from 2.5 to 3.5 ns (FWHM) over the range of pump powers investigated, leading to peak output pulse powers of 28 kW. The lines curves in Fig. 3 are taken from an energetics model based on a recently developed passive Q-switching formalism.[8] In this model fit to our data, both the storage lifetime of the Nd^{3+}:YAG and the ground-state absorption cross section of the Cr^{4+}:YAG at 1064 nm were treated as adjustable parameters. The best agreement between data and model were obtained for 90 μs and 1.55×10^{-18} cm^2 for the storage lifetime and absorption cross section, respectively. This Cr^{4+}:YAG absorption cross section value is generally in agreement with recently published literature values that range from 1.2×10^{-18} to 1.9×10^{-18} cm^2.[9] The small value for the Nd^{3+}:YAG storage lifetime is not surprising for the high specific gains and the high-numerical-aperture gain regions that are characteristic of our WS and corresponds to an amplified spontaneous emission multiplier of 2.86, assuming a 257-μs lifetime in the absence of amplified spontaneous emission. Suppression of amplified spontaneous emission and parasitic modes are important design considerations in the planar WS developed here and are critical for achieving the performance reported herein. We have found it necessary to grind vertical grooves into the polished sides of the WSs between which the pump light is transmitted to suppress parasitic lasing modes. In general, the necessity to groove the sides of the WS presents no problem with pump delivery because of the sub-filled diode-bar apertures that characterize commercially available cw operating laser diode bars. For example, the Coherent diode bars used here for our pump sources have a 30% fill and 150-μm wide emitters centered on 500-μm centers. Using a dicing saw, we placed parasitic suppression grooves along the pump-input sides of the WS, between diode emitters, without affecting pump delivery. The output of this laser was observed to be TM polarized with greater

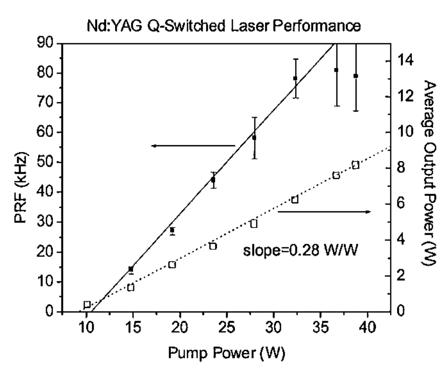

Fig. 3. Average output power and output pulse PRF from a passively Q-switched Nd:YAG CPPWL as a function of the delivered pump power. The pump power is corrected for the Fresnel losses that are incurred at the uncoated sides of the WS.

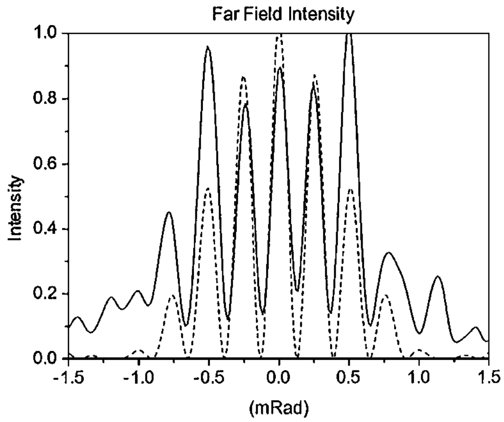

Fig. 4. Solid curve, measured far-field intensity in the unguided dimension from the strip unstable resonator. Dashed curve, expected far-field from a uniformly filled strip unstable resonator aperture but with a 100% reflective central spot on the OC, as described in the text.

than 90% purity. This polarization is perpendicular to the observed polarization from the cw Yb:YAG system. It is known that both the stress induced in the YAG layers during fabrication of the WS and the crystallographic orientation of the Cr^{4+}:YAG (Ref. 10) affect the polarization of the developed laser radiation; however, we have not yet fully analyzed these mechanisms.

Based on our energetic models of the systems described above, we expect the output power to be optimal with OC reflectivities near 0.2. These large output-coupling values are compatible with the requirements of strip unstable resonators, which should permit good beam quality to be generated in the unguided dimension. To illustrate the potential for cleaning up the beam in the unguided dimension, we have demonstrated a strip unstable resonator by polishing a concave 20-cm radius of curvature into the output end of a cw Nd:YAG WS, i.e., a Nd:YAG WS as described above but without a passive Q switch. The HR end of the structure was kept flat. These choices for mirror curvature result in an unstable resonator with a geometric cavity magnification of 1.56. The optical coating applied to the curved OC end of this structure consisted of a 0.70 reflectivity coating over the central 64% of the end face (0.64 = 1/magnification) and an antireflection coating everywhere else. The solid curve in Fig. 4 shows the measured far-field beam intensity in the unguided dimension from this structure. The deep modulation in this intensity pattern demonstrates the high degree of coherence across the 5-mm-wide aperture. The dashed curve in Fig. 4 represents the expected far-field intensity distribution that would be seen from this strip unstable resonator if the output aperture were uniformly filled and there were a 100% reflectivity spot in the center of the OC. The optimum OC reflectivity of $\sim$0.2 for these systems corresponds to a cavity magnification of 5× for a strip unstable resonator with a 100% reflectivity spot in the center of the OC. Going to a cavity magnification of 5× should result in a far field characterized by only three dominant lobes and an M^2 value of $\sim$2.

In conclusion, we have demonstrated a diode-pumped Yb:YAG CPPWL generating greater than 12 W of cw output power. This represents improvements by a factor of 3.5 in the average power and by a factor of 2.2 in optical–optical efficiency compared earlier demonstrations of CPPWL systems.[3] For the first time to our knowledge, we have demonstrated a passively Q-switched CPPWL by using a Nd:YAG gain element and a monolithically incorporated Cr^{4+}:YAG Q switch. This system has demonstrated greater than 8 W of repetitively pulsed Q-switched average output power in short 2.5-ns duration pulses. Finally, we have for what we believe is the first time demonstrated the use of an unstable strip resonator with a CPPWL, showing the potential for achieving high beam quality in both the guided and the unguided dimensions from CPPWL systems. The results reported here have demonstrated the high efficiency that is possible from compact and robust packages with the CPPWL approach as well as the ability to generate linearly polarized output radiation. Such systems will have relevance to applications that involve both marking and nonlinear optical generation.

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