Saturable Bragg reflector self-starting passive mode locking of a Cr^{4+}:YAG laser pumped with a diode-pumped Nd:YVO_4 laser

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We demonstrate self-starting passive mode locking of a Cr^{4+}:YAG laser, using an intracavity nonlinear mirror as a saturable absorber. The pump source is a diode-pumped Nd:YVO_4 laser. Output pulses are centered at 1541 nm, with 26-nm spectral bandwidth and 110-fs pulse width. Output powers of 70 mW are obtained with 8 W of pump power. This mode locking technique is compared with Kerr-lens mode locking.

Utilizing the Kerr effect as a mode-locking mechanism, most notably the Kerr-lens mode-locked (KLM) Ti:sapphire laser operating near the 850-nm region, has dramatically advanced the progress of ultrafast pulse sources at many wavelengths.[1,2] For telecommunications applications, researchers have sought broadband laser media operating in the 1300- and 1550-nm wavelength regimes. In 1991 Shestakov *et al*. reported the first-room temperature cw lasing in Cr^{4+}:YAG.[3] This medium has its gain peak at 1450 nm and produces tunable output from 1380 to 1620 nm. Its absorption is centered about 1000 nm and is similarly broad.[4] The gain coefficient for Cr^{4+}:YAG is relatively low; however, output powers of 1.35 W can be obtained with 8 W of pump power. Similar to the Ti:sapphire laser, the Cr^{4+}:YAG crystal itself can be used as the Kerr medium for KLM operation, and pulses as short as 46 fs have been obtained.[5,6] We report self-starting passive mode locking of a Cr^{4+}:YAG laser, using an intracavity low-loss epitaxially grown semiconductor saturable Bragg reflector (SBR). The SBR functions as a nonlinear mirror with saturable absorption. However, SBR mode locking is self-starting, unlike KLM operation.

Mode locking with a SBR was recently demonstrated by Tsuda *et al*.; a Cr:LiSAF laser was mode locked at 865 nm, producing 100-fs pulses.[7] Brovelli *et al*. have discussed similar structures, using low-temperature grown GaAs.[8] For the Cr^{4+}:YAG laser, operating at 1550 nm, a SBR was fabricated with an AlAs/GaAs Bragg reflector having a broadband reflectivity centered at 1550 nm. The reflectivity was 99.5%, with a bandwidth of 150 nm. Two uncoupled 6-nm-wide $In_{0.52}Ga_{0.48}As$/InP quantum wells separated by 7 nm and located 15 nm from the top surface of the sample provide the saturable absorption required for initiation of mode locking. Because of the decreased absorption coefficient of the InGaAs quantum wells (in comparison with GaAs used by Tsuda *et al*.), two wells were used. The structure of the SBR is shown in Fig. 1(a).

The Cr^{4+}:YAG laser cavity is an astigmatically compensated, folded-Z configuration [Fig. 1(b)]. A Brewster-cut 20 mm $\times$ 5 mm Cr^{4+}:YAG crystal rod, purchased from IRE-Polus, was wrapped in indium foil and clamped in a water-cooled ($\sim$20 °C) copper heat sink. All mirrors have reflectivities centered about 1550 nm, with the folding mirrors having 10-cm radii of curvature. For cw operation a maximum output power of 1.35 W with 8 W of pump was obtained with 1.5% output coupling and a pump threshold around 1.5 W. In one arm, two fused-silica prisms provide group-velocity dispersion compensation with a tip-to-tip separation of 17 cm. A 10-cm radius-of-curvature high reflector at the end of the nondispersive arm focuses the cavity mode onto the surface of the SBR, to an approximate 10-μm-diameter spot. The SBR is soldered to a copper heat-sink mount. A 4-μm-thick pellicle, placed near Brewster's angle in the nondispersive arm, provides variable output coupling. The Nd:YVO_4 pump laser, from Spectra-Physics OEM, is pumped by two 20-W diode arrays, fiber coupled to the laser head. The diffraction-limited pump beam

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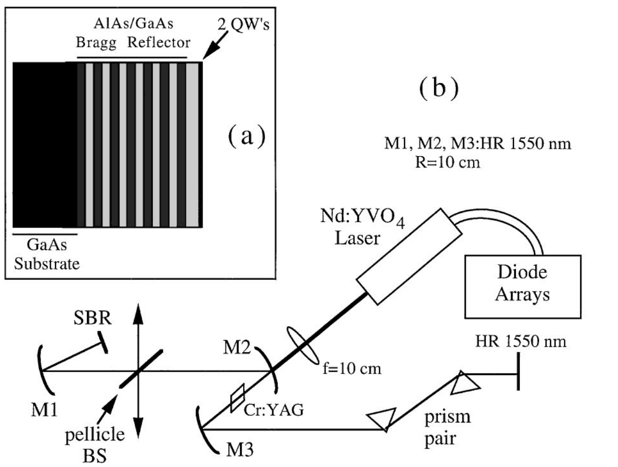

Fig. 1. (a) Diagram of the SBR structure. (b) Diagram of the SBR mode-locked cavity. The cavity mode is focused onto the SBR with a 10-cm-radius mirror. A 4-μm-thick pellicle is used as a variable-output coupler. M's, mirrors; BS, beam splitter; HR, highly reflecting; QW's, quantum wells.

from the Nd:YVO_4 laser is focused into the crystal through one of the folding mirrors by a lens pair with an effective focal length of 10 cm.

Pumping with 8 W, we obtained pulses centered at 1541 nm, with 26-nm bandwidth and a pulse width of 110 fs. The passive mode locking is self-starting and continues unless intentionally interrupted. Figures 2(a) and 2(b) show a typical interferometric autocorrelation trace and a spectrum of the output. Alignment of the cavity for short-pulse operation consisted of cw optimization and then adjustment of the separation between the SBR and its focusing mirror to yield the shortest pulses and maximum stability. Varying the output coupling by rotation of the pellicle gave a maximum output power of 35 mW in each output beam. The output coupling is approximately 0.7% into each beam. Changing the separation between the SBR and its focusing mirror resulted in increasing pulse width and output power.

The excitonic absorption edge in the SBR shifts the cw operation from 1500 to 1530 nm in a flat-cavity configuration. As we modified the mode-locked spectral bandwidth by changing the focusing on the SBR, its short-wavelength edge was held fixed by the excitonic absorption. The output spectrum, mode locked with a narrow spectrum, is centered at 1535 nm, whereas in broadband operation the center is shifted to a longer wavelength. Figure 2(b) shows the absorption spectrum of a typical quantum well as well as the output spectra corresponding to output of two different pulse widths, illustrating this shift with increased bandwidth.

KLM operation was obtained by use of a 1.5% output coupler in a flat-cavity configuration. Pulses as short as 85 fs were obtained with a 47-nm bandwidth, centered at 1536 nm. Sub-100-fs KLM operation occurred in the range 1510–1545 nm. Figures 3(a) and 3(b) show an autocorrelation trace and a spectrum of the KLM output. As with other KLM cavity configurations, the operation was not self-starting.

With the SBR in the cavity we believe that the mode-locking mechanism is dominated by the absorption dy-

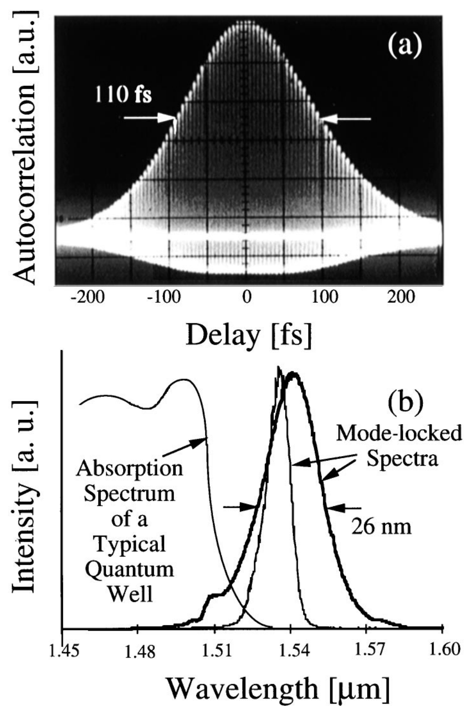

Fig. 2. Interferometric autocorrelation trace of the SBR mode-locked pulses indicating a pulse width of 110 fs. (b) Two spectra of the SBR mode-locked pulses, corresponding to differing pulse widths, superimposed upon a sketch of the approximate absorption of the SBR. 26 nm of bandwidth corresponds to the output of 110-fs pulses.

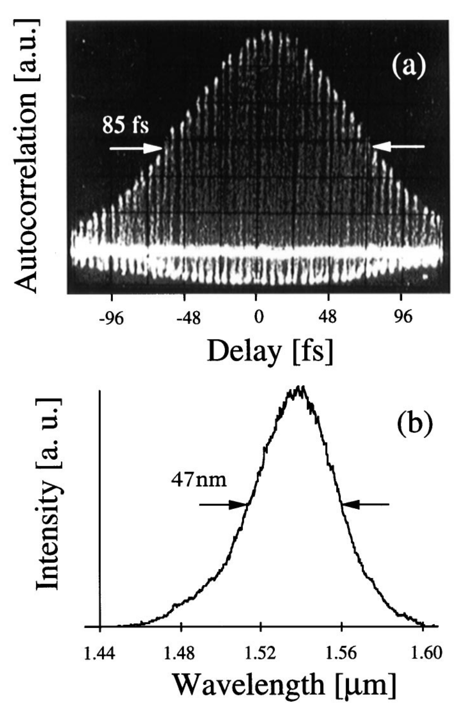

Fig. 3. (a) Interferometric autocorrelation trace of the KLM pulses indicating a pulse width of 85 fs. (b) Spectrum of the KLM pulses.

namics of the SBR. The pulse width obtained with SBR mode locking was never shorter than 110 fs, suggesting that Kerr-lens mode locking, which produces shorter pulses and broader bandwidth, is not the dominant mode-locking mechanism. Additionally, the SBR was replaced with a high reflector at the same position, and Kerr-lens mode locking was exhaustively attempted with no success. The insertion of the SBR did not appear to change the dispersion of the cavity significantly, because optimizing the group-velocity dispersion compensation did not decrease the pulse width. From this, we suggest that the mode-locking mechanism is not SBR-initiated Kerr-lens mode locking.

Mode-locked pulses shorter than 110 fs could not be produced with a SBR having its excitonic absorption peak located at 1500 nm. It is possible that the bandwidth required for sub-100-fs pulses cannot be supported between the excitonic absorption and the falloff of the Cr^{4+}:YAG gain at longer wavelengths. For this reason new SBR samples are being fabricated with exciton peaks at shorter wavelengths. Also, by altering the separation between the SBR and its focusing mirror along with a cavity focusing mirror, we observed that longer pulses could be generated with higher average powers such that the peak power of the pulses was constant. However, 85-fs-wide pulses have been observed with Kerr-lens mode locking at these power levels. This behavior suggests that the mode-locking mechanism is less effective at increased peak powers. This effect may be the result of increased excited carrier densities or saturation of the quantum wells in the SBR. Increasing the spot size on the SBR by using a longer-focal-length focusing mirror and thus decreasing the intensity on the SBR may counteract this problem and yield shorter pulses at higher output powers.

In conclusion, we have built a self-starting passively mode-locked Cr^{4+}:YAG laser pumped by a diode-pumped Nd:YVO_4 laser. We achieved the mode locking by simply inserting the SBR, as a nonlinear mirror, into the laser cavity. The output, centered at 1541 nm, has a spectral bandwidth of 26 nm, with 110-fs pulse widths and a total average power of 70 mW.

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