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Oxidized GaAs/AlAs mirror with a quantum-well saturable absorber for ultrashort-pulse Cr^{4+}:YAG laser

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Abstract

Ultra-broadband saturable Bragg reflectors consisting of a 7-period GaAs/Al_xO_y Bragg mirror and an InGaAs/InP quantum well were studied and used to start modelocking of 36 fs pulses near 1500 nm in a dispersion compensated Cr^{4+}:YAG laser. The mirrors are comprised of high-index-contrast GaAs/Al_xO_y Bragg stacks grown as GaAs/AlAs and oxidized to create mirror areas as wide as 300 μm. They exhibit non-saturable losses smaller than 0.8% and a stopband from 1300 to 1800 nm, indicating the potential for the generation of shorter pulses.

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Kerr lens modelocked Cr^{4+}:YAG lasers are used to generate femtosecond laser pulses in the wavelength range from 1300 to 1600 nm. Pulses as short as 20 fs, with spectral bandwidths of 190 nm FWHM, have been produced from a laser which uses double-chirped mirrors (DCMs) for high-order dispersion compensation [1]. Using only fused silica prisms for group delay dispersion (GDD) compensation, 43 fs pulses with a spectral bandwidth of 80 nm have been generated [2]. In general, however, Kerr lens modelocking (KLM) in these lasers is not typically self-starting without precise alignment of the laser cavity.

Semiconductor saturable absorber mirrors, capable of initiating modelocking without sensitive alignment, have been used to overcome this difficulty in a variety of solid-state lasers [3–5]. In

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Cr^{4+}:YAG lasers, modelocking has been demonstrated with saturable absorber mirrors consisting of InGaAs/InP [6], InGaAs/GaAs [7], or InGaAs/InAlAs [8,9] quantum wells absorbing near 1550 nm grown upon a highly reflecting mirror. In each of these cases, GaAs/AlAs Bragg stacks were used as the mirror substrate. These mirrors have a maximum bandwidth of ~150 nm which prevents generation of shorter pulse durations. To overcome this problem, Zhang et al. used an InGaAs/InAlAs quantum-well absorber bonded onto a gold mirror to generate 44 fs pulses from a Cr^{4+}:YAG laser. Because the intrinsic loss of the gold mirrors was too large for the loss-sensitive Cr^{4+}:YAG laser, the gold mirror reflectivity was enhanced by $SiO_2/TiO_2/SiO_2$ dielectric layers [10,11]. It is likely that the pulsewidth in this laser was limited by higher-order dispersion rather than the mirror bandwidth.

In this paper, we report the use of a novel high-index-contrast mirror-based saturable Bragg reflector (SBR) to generate 36 fs pulses with a FWHM bandwidth of 68 nm in a Kerr lens modelocked Cr^{4+}:YAG laser. Broadband oxidized mirrors, not previously used in laser cavities other than VCSELs, have extremely low-mirror losses over a bandwidth as large or larger than enhanced metallic mirrors. The combination of a broadband SBR with a stopband from 1300 to 1800 nm and DCMs for dispersion compensation have enabled the generation of the ultrashort Cr^{4+}:YAG pulses reported here.

The refractive index and square of the electric field standing wave pattern in the high-dielectric contrast SBR are shown as a function of position in Fig. 1. The SBR consists of a 7-period GaAs/Al_xO_y Bragg stack and a 10 nm InGaAs quantum well in a $\lambda/2$-thick InP layer, where each layer thickness is chosen for a center wavelength of 1440 nm. The refractive indices of GaAs and Al_xO_y at 1.5 μm are 3.39 and 1.61, respectively. It is therefore possible to create mirrors with a calculated reflectivity of >99.9% over the wavelength range 1220–1740 nm and >99.99% over the range 1300–1600 nm with only 7 periods of the high-index contrast materials.

The SBRs are fabricated with III–V semiconductor growth techniques. First, the GaAs/AlAs multilayer stack and InGaAs quantum well within an InP cladding layer are grown by gas source molecular beam epitaxy (GSMBE). Following growth, the AlAs layers are converted to Al_xO_y through a wet-oxidation process [12]. The SBR is placed within a wet-oxidation furnace at 400 °C. Because the oxidation process converts high-index AlAs to low-index Al_xO_y laterally from the edge of the structure, only material near an exposed edge will oxidize. After 9.5 h of oxidation, the resulting Al_xO_y layers extended as far as 300 μm into the structure, resulting in a larger oxidized area than previously used in VCSELs. Cross-sectional scanning electron micrograph (SEM) images of typical unoxidized and oxidized SBR structure are shown in Figs. 2(a) and (b). The irregular appearance of the polycrystalline Al_xO_y shown in Fig. 2(b) is due primarily to the cleaving. No delamination of the layers is apparent.

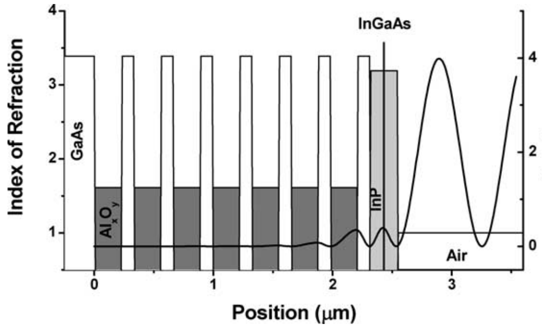

Fig. 1. Index of refraction and electric field squared of the designed saturable Bragg reflector (SBR) mirror.

The SBR's optical properties were studied using several techniques. Mirror reflectivity was recorded using Fourier transform infrared spectroscopy (FTIR), and is shown in Fig. 3. The measurement was taken with a commercial FTIR (MagmaIR 860, Nic Plan Microscope) at a 35 degree angle of incidence, leading to a wavelength shift of ~5%. Qualitatively, the SBR has a stopband from 1300 to 1800 nm. It is difficult to determine an exact reflectivity from FTIR. The SBR non-saturable loss is estimated to be <0.8% by determining the laser threshold for several output couplers (Findlay–Clay analysis). Furthermore, an absolute reflectivity greater than 99% is infered by

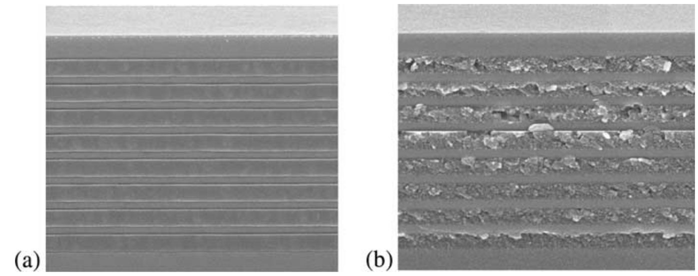

Fig. 2. Scanning electron micrograph (SEM) images of an (a) unoxidized and (b) oxidized SBR structure. Through oxidation, the AlAs layers are converted to Al_xO_y.

the successful use of the mirror in the low-gain Cr^{4+}:YAG laser itself. Photoluminescence was used to observe emission centered at 1540 nm from the 10 nm InGaAs quantum well within the InP cladding layer. Pump-probe spectroscopy, using 150 fs pulses from an optical parametric oscillator, was employed to study the absorber's saturation characteristics at 1540 nm. At low fluences, the SBR response shows a fast saturation due to spectral hole burning and a long recovery time of about 40 ps due to recombination. The saturation fluence is estimated to be on the order of $\sim$10 $\mu J/cm^2$, and the maximum saturable loss is 0.3%. As the pump fluence is increased, significant two-photon absorption (TPA) reduces the SBR's net saturable loss [13]. At high-peak intensities, the loss from TPA may limit the peak power of the pulses and affect the minimum achievable pulse-width.

The broadband SBR was placed within a Cr^{4+}:YAG laser cavity to initiate modelocking. A diagram of the laser cavity is shown in Fig. 4. The laser cavity consists of a 2 cm Cr^{4+}:YAG laser rod supplied by A.V. Shestakov of E.L.S. company, pumped at 1064 nm by a Spectra-Physics 11 W $Nd:YVO_4$ laser. The pump beam is focused into the crystal through a 10 cm focal length lens. About 5 cm to both sides of the laser crystal are 10 cm radius of curvature DCMs (M1 and M2) rotated 16° from normal incidence to compensate the astigmatism of the Brewster–Brewster cut laser rod. One arm of the cavity contains an output coupler (OC) (0.7% at 1515 nm and <1.4% transmission from 1420 to 1630 nm) while the

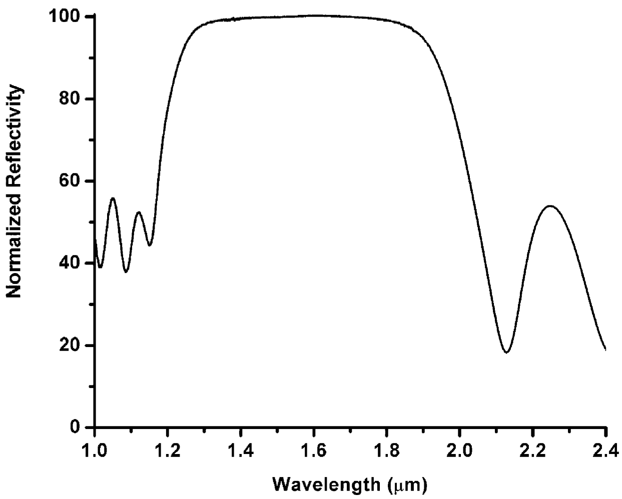

Fig. 3. Reflectivity of the saturable Bragg reflector (SBR) measured using Fourier transform infrared spectroscopy.

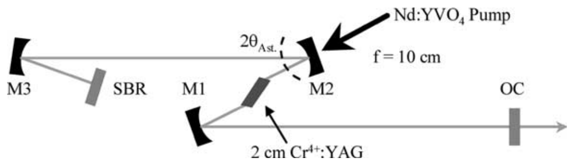

Fig. 4. Schematic of a Cr^{4+}:YAG laser cavity consisting of three 10 cm radius of curvature double-chirped mirrors (M1–M3), an output coupler (OC), and a saturable Bragg reflector (SBR) end mirror.

second cavity arm contains a 10 cm radius of curvature DCM (M3) focusing onto an SBR. The curved DCM focuses the cavity mode to a ~50 μm beamwaist on the SBR. By changing the radius of curvature of M3, the fluence on the SBR could be varied. In practice, however, the spot size must be small enough to fit within the oxidized region. The laser cavity is designed to have 6 DCM reflections each cavity round-trip to compensate the GDD of the Cr^{4+}:YAG crystal. Details of the dispersion compensation by DCMs have been described previously [1].

The laser had an output power of 300 mW with the SBR and 600 mW without the SBR for 9 W of absorbed pump. No damage to the SBR was observed during laser operation. Using the SBR, the laser was modelocked and could be tuned from 1400 to 1525 nm with an intracavity birefringent filter. The short wavelength limit of 1400 nm was due to roll-off of the output coupler (OC3) reflectivity. When the birefringent filter was removed, the laser could be aligned to optimize KLM. The curved mirror separation (between mirrors M1 and M2) and the laser crystal position were varied to maximize the spectral bandwidth and minimize the pulsewidth. KLM was only possible when the cavity was enclosed in plastic tubes and purged with dry nitrogen gas to remove water vapor from the air. This water vapor adds intracavity absorption and dispersion that eliminates the possibility of KLM at wavelengths shorter than 1500 nm.

A plot of the KLM pulse spectrum, measured by an optical spectrum analyzer, is shown on linear and logarithmic scales in Fig. 5(a). The pulse spectrum is centered at 1490 nm and has a full-width half maximum of 68 nm. Spectral components are detected from 1200 to >1700 nm, the limit of the optical spectrum analyzer. An autocorrelation, measured by a fringe-resolved TPA autocorrelator [14], is shown in Fig. 5(b). Assuming a sech-shaped pulse, the autocorrelation yields a pulsewidth of 32 fs. However, a sech-shaped pulse fit can underestimate the actual pulsewidth for non-sech-shaped pulses. The measured spectrum corresponds to 36 fs bandwidth limited pulses.

There is no fundamental reason why the pulsewidth should be limited to 36 fs. It is likely that TPA in the saturable absorber limits the pulsewidth in this laser when Kerr lens modelocked [15]. Increasing the spot size on the SBR would lower the intensity, and therefore TPA, for a given power. The fabrication of larger oxidized

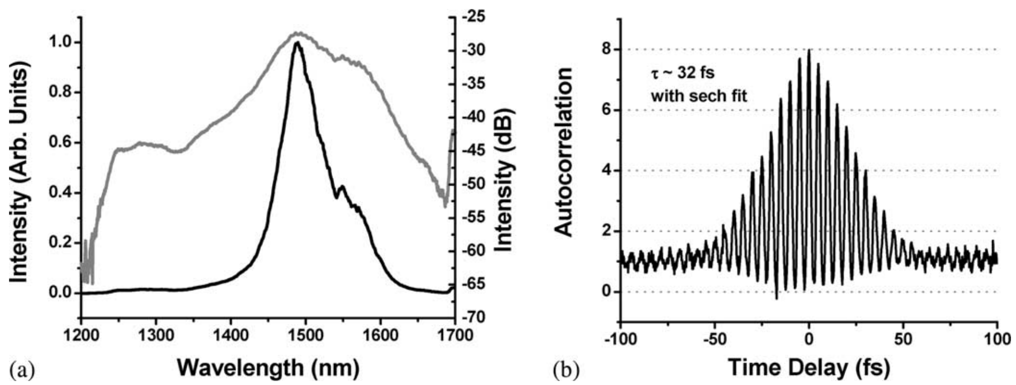

Fig. 5. (a) Pulse spectrum from a self-started Cr^{4+}:YAG laser plotted on a linear (black) and logarithmic (gray) scale. (b) Interferometric autocorrelation of a self-started Cr^{4+}:YAG laser.

regions should make it possible to achieve shorter pulses.

For the first time, an oxidized broadband $GaAs/Al_xO_y$ mirror-based InGaAs/InP quantum-well SBR was used to start modelocking of a Cr^{4+}:YAG laser. The mirror had a stopband from 1300 to 1800 nm and was capable of starting 36 fs pulses with a spectrum centered at 1490 nm and a bandwidth of 68 nm FWHM. The mirrors were epitaxially grown and oxidized to create a high-index-contrast broadband mirror over relatively large dimensions ($\sim$300 μm).

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References

[1] D.J. Ripin, C. Chudoba, J.T. Gopinath, J.G. Fujimoto, E.P. Ippen, U. Morgner, F.X. Kärtner, V. Scheuer, G. Angelow, T. Tschudi, Opt. Lett. 27 (2002) 61.
[2] Y.P. Tong, P.M.W. French, J.R. Taylor, J.G. Fujimoto, Opt. Commun. 136 (1997) 235.
[3] U. Keller, K.J. Weingarten, F.X. Kärtner, D. Kopf, B. Braun, I.D. Jung, R. Fluck, C. Hönninger, N. Matuschek, J. Aus der Au, IEEE J. Select. Top. Quant. Electron. 2 (1996) 435.
[4] S. Tsuda, W.H. Knox, S.T. Cundiff, W.Y. Jan, J.E. Cunningham, IEEE J. Select. Top. Quant. Electron. 2 (1996) 454.
[5] S. Schön, L. Gallmann, M. Haiml, U. Keller, Proceedings of CLEO, paper CWB2 (2001) 314.
[6] B.C. Collings, J.B. Stark, S. Tsuda, W.H. Knox, J.E. Cunningham, W.Y. Jan, R. Pathak, K. Bergman, Opt. Lett. 21 (1996) 1171.
[7] S. Spälter, M. Böhm, M. Burk, B. Mikulla, R. Fluck, I.D. Jung, G. Zhang, U. Keller, A. Sizmann, G. Leuchs, Appl. Phys. B 65 (1997) 335.
[8] M.J. Hayduk, S.T. Johns, M.F. Krol, C.R. Pollock, R.P. Leavitt, Opt. Commun. 137 (1997) 55.
[9] Y. Chang, R. Maciejko, R. Leonelli, A.S. Thorpe, Appl. Phys. Lett. 73 (1998) 2098.
[10] Z. Zhang, T. Nakagawa, K. Torizuka, T. Sugaya, K. Kobayashi, Opt. Lett. 24 (1999) 1768.
[11] Z. Zhang, T. Nakagawa, K. Torizuka, T. Sugaya, K. Kobayashi, Appl. Phys. B 70 (2000) S59.
[12] K.D. Choquette, K.M. Geib, C.I.H. Ashby, R.D. Twesten, O. Blum, H.Q. Hou, D.M. Follstaedt, B.E. Hammons, D. Mathes, R. Hull, IEEE J. Select. Top. Quant. Electron. 3 (1997) 916.
[13] E.R. Thoen, E.M. Koontz, M. Joschko, P. Langlois, T.R. Schibli, F.X. Kärtner, E.P. Ippen, L.A. Kolodziejski, Appl. Phys. Lett. 74 (1999) 3927.
[14] D.T. Reid, W. Sibbett, Opt. Photon. News 19 (1998).
[15] J.T. Gopinath, E.R. Thoen, E.M. Koontz, M.E. Grein, L.A. Kolodziejski, E.P. Ippen, J.P. Donnelly, Appl. Phys. Lett. 78 (2001) 3409.