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High-average-power (>20-W) Nd:YVO₄ lasers mode locked by strain-compensated saturable Bragg reflectors

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Strain-compensated double InGaAs quantum-well saturable Bragg reflectors (SBR's) with high damage thresholds have been developed for use as mode-locking elements in high-average-power neodymium lasers. Nd:YVO₄ lasers have been developed with these new SBR's, which produce transform-limited pulses of 21-ps duration at 90 MHz and an average power of 20 W in a diffraction-limited output beam. The peak pulse power at an output power of 20 W was 10.6 kW. A comparison of the operating parameters of strained single and strain-compensated double-well SBR's indicates that the damage threshold increased by a factor of at least 2–3. Long cavity laser variants were investigated to assess the limitations of further power scaling. At a repetition frequency of 36-MHz stable mode-locked pulses with peak pulse powers of 24.4 kW and pulse energies of 0.6 μJ could be generated. © 2000 Optical Society of America [S0740-3224(00)02706-5]

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1. INTRODUCTION

In recent years there has been significant research interest in the use of semiconductor-based saturable absorbers to produce ultrashort optical pulses from solid-state laser sources¹ (see also Refs. 2, 3, and references therein). It has been shown that by configuration of a suitable semiconductor saturable absorbing layer within a semiconductor Bragg stack a practical integrated passive mode-locking mirror can be produced. A few notable examples of moderate (<5-W) average output power systems^{4,5} have been demonstrated; however, saturable absorber device details were limited. Average output powers of as great as 8 W have been demonstrated in a Yb:YAG system.⁶ Recently, 10.7-W output power was demonstrated from a Nd:YAG laser system mode locked with an antiresonant Fabry–Perot saturable absorber device.⁷ The limited device lifetime, which was of the order of 40 hours, was reported to be due to residual unsaturable absorption within the absorbing layer. However, typically semiconductor saturable absorbers have been applicable only to low-average-power (<1-W) lasers, owing to catastrophic optical damage.

Our approach to passive mode locking of neodymium-doped lasers is to operate above the *Q*-switching mode-locking threshold and hence obtain stable operation⁸ and not to suppress self-*Q*-switching by affecting the device properties by the introduction of defects. The main concern with power scaling of the mode-locked laser is then simply to reduce the unsaturable background losses of the saturable absorber device such that the high-energy self-*Q*-switching cannot induce damage.

In this paper the basic saturable Bragg reflector (SBR)

design considerations and device properties pertinent to operation at 1.064 μm are outlined in Section 2. Section 3 describes the design principles employed in the construction of a side-pumped, high-average-power, single-transverse-mode Nd:YVO₄ laser, which is the basis of all the mode-locked laser variants discussed subsequently. In Section 4, a temperature-tuning study of a simple single-quantum-well (SQW) SBR mode-locked Nd:YVO₄ laser is detailed, because this serves to elucidate the key features and limitations of high-power SBR mode-locked lasers. A new strain-compensated SBR device that overcomes the damage limitations of previous devices is introduced in Section 5. High-power (>20 W) passively mode-locked laser configurations featuring these saturable absorbers, and the limits to further power scaling, are addressed in Section 6.

2. PROPERTIES OF SATURABLE BRAGG REFLECTORS

In_xGa_{1-x}As is, at present, the most suitable material for use as the absorbing layer within semiconductor saturable absorber mirrors compatible with 1-μm neodymium-doped lasers. For a compressively strained In_xGa_{1-x}As quantum-well (QW) grown on GaAs the *e*1 – *hh*1 transition energy can be varied from 1.42 eV (870 nm) to ~1.14 eV (~1090 nm) by variation of the indium concentration.⁹ The long-wavelength end of this range can be accessed only by use of high (>30%) indium concentrations in conjunction with narrow (<7 nm) quantum wells. To fabricate SQW SBR's suitable for use at 1064 nm,⁸ we used a 10-nm saturable absorber layer com-

posed of $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ embedded within the topmost layer of a 30 pair $\text{GaAs}/\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ Bragg stack. The structure was grown by nonrotated metal-organic chemical-vapor deposition (MOCVD),¹⁰ and a typical map of the reflectivity across the 2-in. ($\sim 5\text{-cm}$) -diameter wafer is shown as Fig. 1. This device was highly strained, and in fact the strain–thickness product ($\sim 180 \text{ \AA}\%$) for the QW was very close to the accepted critical value of the strain–thickness product^{11,12} of $200 \text{ \AA}\%$. The surface quality of the wafer and the high reflectivity of the device, coupled with its performance at 1064 nm, indicated that the MOCVD growth was uniform without significant strain relaxation. However, as is detailed below, the damage threshold was significantly lower than that obtained for a strain-balanced structure.

3. LASER CONFIGURATIONS

The basic laser configuration used to assess the performance of the SBR devices is shown in Fig. 2. The $2 \text{ mm} \times 2 \text{ mm} \times 12 \text{ mm}$ Brewster-angled Nd:YVO_4 slab had a 1.1% neodymium concentration and was antireflection coated for $\sim 808 \text{ nm}$ on its long faces to minimize pump reflection. The laser slab was sandwiched (top and bottom) between two water-cooled copper blocks covered with indium foil. Fast-axis collimated 1-cm diode laser

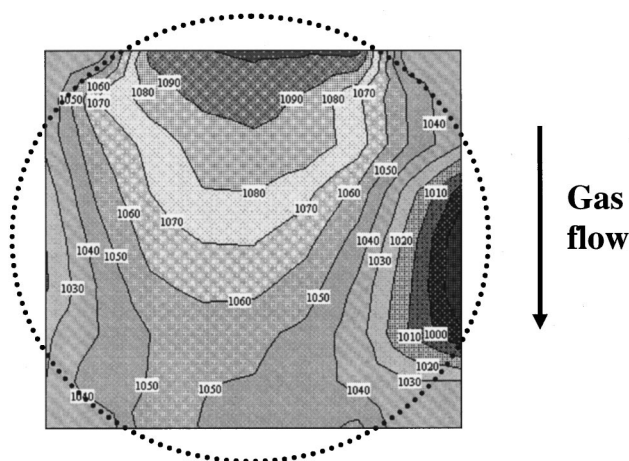


Fig. 1. Reflectivity map for typical SBR wafer. Dotted circle indicates the position of the 2-in. wafer. The values shown relate to the center of the reflectivity passband. The bandwidth of the reflectivity passband was $\sim 80\text{--}100 \text{ nm}$.

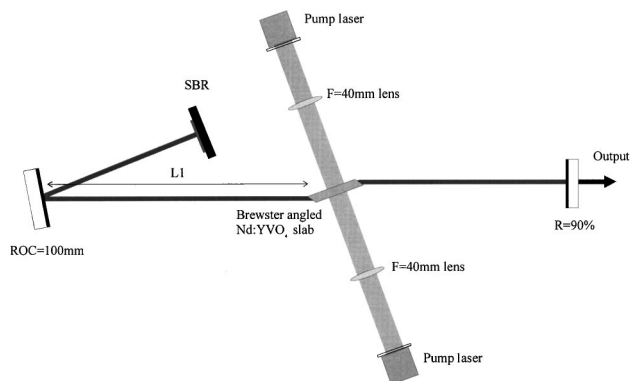


Fig. 2. Basic SBR mode-locked Nd:YVO_4 laser configuration.

bars were lens coupled to the Nd:YVO_4 slab by use of 40-mm spherical lenses. The pump lasers delivered $\sim 17 \text{ W}$ to the crystal when temperature tuned to emit at $\sim 808 \text{ nm}$, of which $\sim 75\%$ was absorbed. A sheet of gain of $10 \text{ mm} \times 2 \text{ mm} \times \sim 250 \mu\text{m}$ was thus excited within the Nd:YVO_4 slab. The reflectivity of the output coupler was 90%. From this configuration, single-transverse-mode operation was obtained for an output power level as great as 4.5–5 W when only one diode laser array was used. This value could be increased by use of two pump lasers; however, strong thermal lensing limited the maximum single-mode output power to only 6.5 W.

4. TEMPERATURE TUNING

The SBR was mounted onto a thermoelectric device capable of varying the temperature of the device within the range $10\text{--}80 \text{ }^\circ\text{C}$. The low-temperature end of the temperature range was limited by condensation. If water droplets formed on the device when cooled, the laser power would turn off; however, when the device was dried, the laser performance was restored. Flowing, say, dry nitrogen gas over the sample would reduce the dew point and effectively extend the minimum low-temperature operating point if required; however, for the SBR devices used in this study the accessible temperature range proved to be adequate.

The effects of tuning the temperature of the SBR³ are best discussed with reference to the experimental results obtained for an optimized single-diode-array-pumped short-cavity Nd:YVO_4 laser mode-locked with a single In-GaAs QW SBR, since this will elucidate the general operational characteristics of SBR mode-locked lasers.

The outputs of SBR mode-locked lasers follow a general characteristic behavior as a function of the pump power delivered to the laser.¹³ At, or just above, oscillation threshold the output is effectively continuous wave (cw) in nature; increased pumping initiates a mode-locked pulse state that is 100% modulated by a relaxation–oscillation-driven Q -switched pulse envelope. The frequency of the Q -switched envelope increases and its width reduces as the pump power is increased. This is in accordance with the pump power dependence of the relaxation–oscillation resonance frequency and the small signal gain. This state is termed the Q -switched mode-locked state. At some higher pump power the Q -switched mode-locked state is transformed into a pure mode-locked state with no long-term modulation. For the lasers discussed here the transition from the Q -switched mode-locked to the quiet mode-locked state occurs over only a small range of output power, say, $<0.1 \text{ W}$. Therefore the transition point is well defined (in terms of average output power) and is referred to here as the Q -switched mode-locked transition power.

The relative spectral position of the quantum-well exciton peak of the SQW SBR and the laser wavelength were well suited to show the key temperature-tuning effects with the temperature range available at this time. This laser was capable of producing as much as 6.4 W of average power with typical pulse durations in the range of $\sim 30\text{--}40 \text{ ps}$ but was operated at just over 3-W average power for these measurements.

The temperature-tuning characteristics of the SBR mode-locked laser are shown in Fig. 3. Two general trends can immediately be seen from Fig. 3: The output power corresponding to the transition between the Q -switched mode-locked state to the stable mode-locked state increased as the SBR temperature was increased (see Fig. 3 inset). Also, the pulse duration was reduced as the temperature was increased. These effects occur because here the exciton absorption resonance is at a shorter wavelength than the laser emission. As the temperature of the SBR increases, the absorption peak shifts

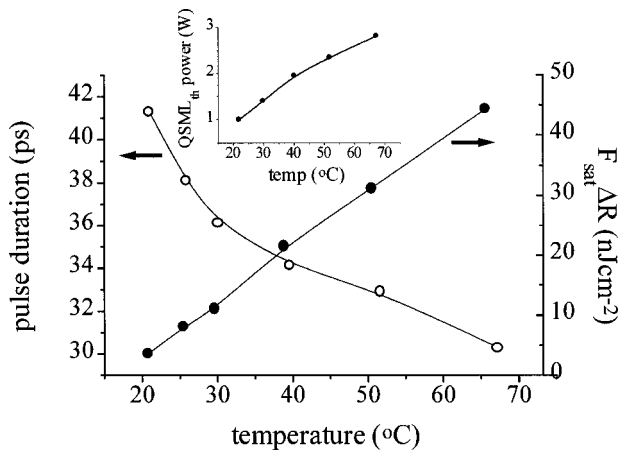


Fig. 3. Temperature-tuning characteristics of a typical single InGaAs QW SBR mode-locked laser. The cavity frequency was 445 MHz.

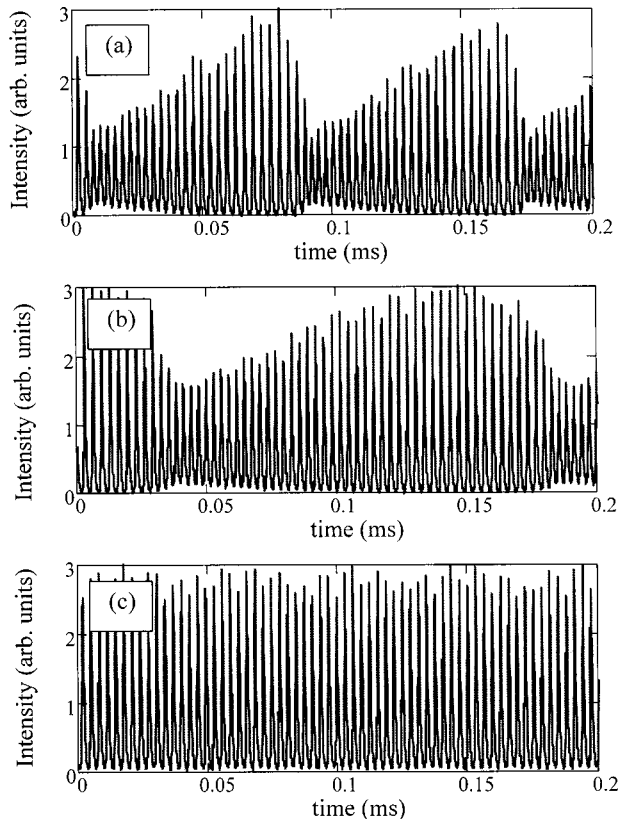


Fig. 4. Q -switched mode-locked waveforms recorded at (a) 2.1-W, (b) 2.2-W, and (c) 2.3-W average output power. The transition to stable mode locking was 2.35 W.

to longer wavelengths (at ~ 0.3 nm/°C); thus the laser experiences greater saturable absorption and so increased modulation depth. The calculated values of $F^{\text{sat}}\Delta R$ (as detailed in Ref. 13, Hönninger *et al.*) versus temperature are also shown in Fig. 3. These data are useful for the comparison of the underlying saturable absorption properties of different saturable absorber structures and devices.

If the Q -switched mode-locked state was accessed for average output powers of greater than ~ 3 –3.5 W, catastrophic optical damage would occur. This corresponded to 30–35-W incident power on the SBR in a focal spot of ~ 60 $\mu\text{m} \times 90$ μm . Therefore, for the case shown here, the SBR temperature must be kept below ~ 80 °C. However, once the laser entered the stable mode-locked state, the output power could be increased up to 4.5 W when one pump is used, or 6.4 W for the two-pump laser configuration.

It is worth noting that closer examination of the Q -switched mode-locked state temporal envelope (see Fig. 4) reveals that the characteristics of the Q -switched mode-locked output is stable only at output powers very close (a few hundred milliwatts) to the Q -switched mode-locked transition power. At low powers the Q -switched pulse energy increases slowly, reaches a maximum, then suddenly drops to a reduced level. The degree of modulation reduces (and the period increases) until it is eliminated at a power just below the transition power. Use of the enhanced peak power of the mode-locked pulses at the peak of the Q -switched envelope therefore cannot be considered to be a serious proposition.

5. STRAIN-COMPENSATED SATURABLE BRAGG REFLECTORS

To scale the average output power from these lasers, it is evident that the damage threshold of the SBR must be increased. Therefore the background unsaturable loss of the device must be reduced. We employed a twofold approach to fabricate devices with lower losses. First, more uniform growth can be affected by reduction of the indium content of the QW, hence further eliminating any possible strain relaxation and defect generation. Because of the reduced indium content, the exciton resonance shifts to shorter wavelengths, and the saturable absorption (and hence modulation depth) at the laser wavelength will be reduced. To reestablish sufficient saturable absorption at the laser wavelength, two QW's were incorporated into the structure instead of a single well. However, the strain of the composite double-well structure is now well above the critical level, and so strain-compensating GaAsP intermediate layers¹⁴ were employed to reduce the total device strain to almost zero.

The SBR structure developed for high-average-power lasers consisted of the following [see Fig. 5(a)]: a GaAs substrate, onto which 29 $\lambda/4n_{\text{hi},10}$ -thick layer pairs of $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}/\text{GaAs}$ were deposited (where $n_{\text{hi},10}$ is the refractive index of the respective layers at the design wavelength); a $\lambda/4n_{10}$ thick layer of $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$, followed by the sequence $\text{GaAs}/\text{GaAs}_{0.7}\text{P}_{0.3}/\text{In}_{0.22}\text{Ga}_{0.78}\text{As}$ QW/ $\text{GaAs}_{0.7}\text{P}_{0.3}/\text{In}_{0.22}\text{Ga}_{0.78}\text{As}$ QW/ $\text{GaAs}_{0.7}\text{P}_{0.3}/\text{GaAs}$ (the

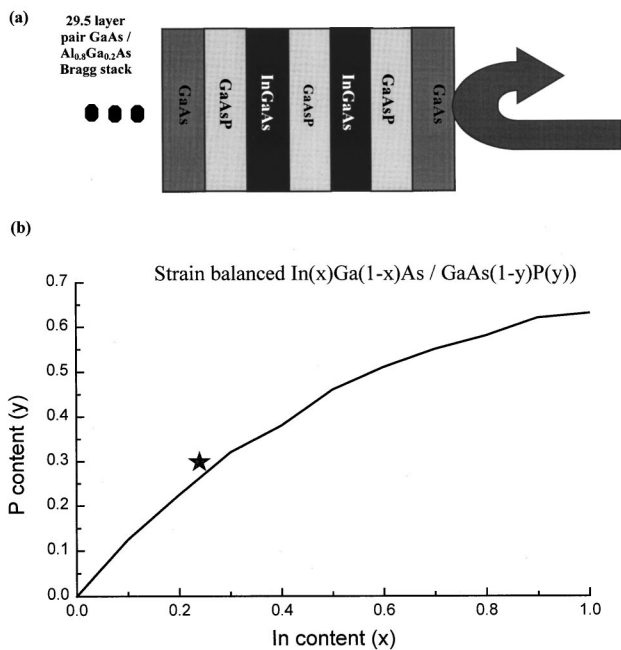


Fig. 5. (a) Schematic of the topmost layers of the strain-balanced InGaAs DQW SBR. (b) Strain compensation with GaAsP layers. The solid curve indicates the relative concentration of indium and phosphorus required to give zero net strain. The star denotes the composition of the strain-compensated SBR devices used in this study.

total thickness of this sequence was equivalent to $\lambda/4$ at the design wavelength of 1064 nm).

The only deviation from a uniform $\lambda/4$ Bragg stack was the two 10-nm InGaAs QW's surrounded by the three GaAsP strain-compensating barrier layers. The device was therefore naturally antiresonant, with no subcavities being present to complicate the filter response. Figure 5(b) shows that 30% phosphorous content was close to that required to balance the strain introduced by the In_{0.22}Ga_{0.78}As QW's.

Alternating layers of Al_{0.8}Ga_{0.2}As/GaAs were chosen instead of AlAs/GaAs, since this simplified the growth of the device. As a consequence of the lower refractive-index contrast, the reflection bandwidth of the device is reduced. However, given the standard layer thickness tolerance limits for MOCVD growth,¹⁵ the overlap of the reflectivity spectrum with the excitonic resonance of the QW's was still ensured.

When the strain-compensated SBR was used in the short 445-MHz laser cavity, similar mode-locked performance to the SQW SBR was obtained. However, at room temperature the *Q*-switched mode-locked transition was at ~ 4.5 W output power. This suggested that the saturable absorption at the laser wavelength was greater than for the SQW device. (By cooling the SBR, the *Q*-switched mode-locked transition could be reduced.) In this cavity configuration it was observed that the double-quantum-well (DQW) SBR experienced no optical damage even when the laser was made to produce a *Q*-switched mode-locked output, by means of increasing the device temperature, up to its maximum output power of 6.4 W. This result implied that the new strain-balanced SBR had a damage threshold more than two times greater than that of the strained SQW SBR.

6. HIGH-AVERAGE-POWER MODE-LOCKED OPERATION

Modal instabilities due to strong thermal lensing within the Nd:YVO₄ laser prevented further power scaling of our SBR mode-locked lasers. To access the power range of tens of watts, the cavity design had to be readdressed specifically to ensure single-transverse-mode operation in the presence of a strong cylindrical thermal lens. The approach we used here was to concentrate on single-transverse-mode power scaling of a generalized short two-mirror cavity. Mode-locked variants could then be constructed by employment of a (de)magnifying lens relay system such that additional cavity components could be used without disrupting the modal properties of the laser. Fast-axis collimated pump diode lasers obtained from Jenoptic (Model JOLD-24-CPFN-1L) with a higher output power of 24 W were also employed in our power scaling experiments. Four pump lasers were imaged with $f = 40$ mm lenses and were arranged as shown in Fig. 6(a).

A simple model, based on the standard *ABCD* propagation matrix method,^{16,17} was developed to calculate the most appropriate cavity optics for high-power single-transverse-mode operation of the Nd:YVO₄ laser. The model calculates the spot sizes, for both the tangential and the sagittal planes, within the crystal and on the end mirrors as a function of the focal length of the thermal

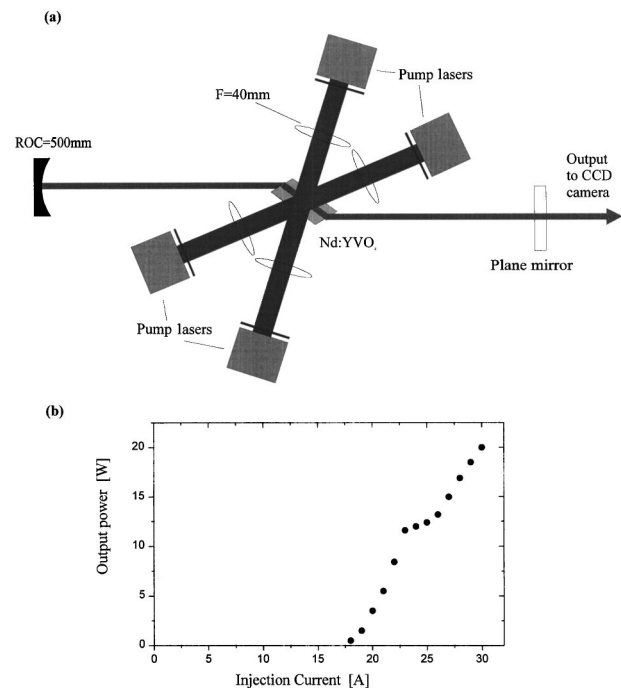


Fig. 6. (a) Short four (24-W) pump Nd:YVO₄ laser cavity. Each pump laser incorporates a fast-axis collimating microlens, and the output is coupled to the Nd:YVO₄ slab with a $f = 40$ mm spherical lens. (b) Power transfer characteristic of the short Nd:YVO₄ laser. The output was single transverse mode for all pump currents. Note that the laser was optimized with the maximum drive current applied to the pump lasers; the measurements shown here were then recorded with no cavity realignment. The kink at ~ 23 – 24 A occurred because the temperature of the pump lasers was optimized at 30-A injection current and not a modal instability.

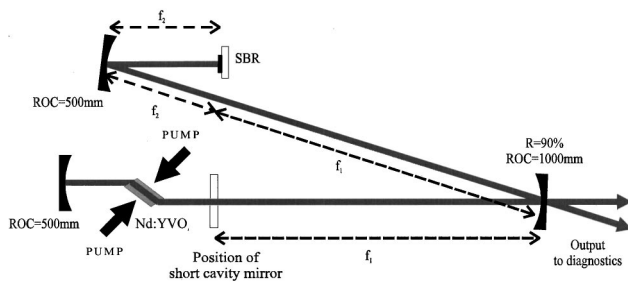


Fig. 7. 90-MHz SBR mode-locked Nd:YVO₄ cavity configuration. Note that the relay optics images the position of the optimized short-cavity plane mirror onto the SBR with a magnification equal to f_2/f_1 .

lens, the curvature of the end mirrors, and the relative position of the mirrors with respect to the crystal. This procedure was repeated for a wide range of cavity optics. In the tangential plane the crystal acts to aperture the intracavity field, whereas in the sagittal plane the height of the pumped region was the important parameter in determining the modal characteristics. From the model a set of cavity optics and their relative positions can then be found that best fit the constraints imposed by the allowed beam size within the crystal. These solutions were also analyzed for their robustness in the presence of a short- and variable-focal-length thermal lens.

The most appropriate cavity was found to consist of a 500-mm radius of curvature (ROC) mirror and a plane mirror [see Fig. 6(a)]. The optimum distance from the crystal was found to be 100 mm for the curved mirror and 70 mm for the flat mirror. In this configuration the laser produced a single-transverse-mode average output power of 20 W for an output coupler reflectivity of 80% and 23 W for $R_{\text{out}} = 70\%$. The power transfer characteristic, for $R_{\text{out}} = 80\%$, is shown in Fig. 6(b), where the temperature of the pump lasers was optimized at the maximum drive current. At low pump powers the spectral overlap of the diode laser emission with the Nd:YVO₄ absorption was nonoptimal; thus the curve obtained deviates from a straight line.

In this configuration the radius of the beam on the flat output coupling mirror was $\sim 270 \mu\text{m} \times 190 \mu\text{m}$. To configure the mode-locked cavity, a 1000-mm ROC mirror was placed 500 mm from the original position of the flat short-cavity mirror. A 500-mm ROC mirror ($R = 90\%$) was then placed at a further 725 mm; the cavity was terminated at a further 250 mm with a flat high-reflectivity mirror, or for mode-locking, the SBR sample (as shown in Fig. 7). With the original short-cavity mirror removed, this cavity is equivalent to a lens relay with a demagnification of two. The beam radius on the SBR was therefore $\sim 135 \mu\text{m} \times 95 \mu\text{m}$. In this way, stable mode locked operation was obtained. The pulse repetition frequency was 90 MHz, and the pulse duration was measured as 21 ps at a total average output power of 20.0 W (see Fig. 8). The pulse peak power was therefore 10.6 kW. The pulse duration varied slightly as a function of power from 23.4 ps at 15-W output, to 22.2 ps at 18 W, to 20.9 ps at the maximum output power of 20 W (fluence on the SBR, $F_{\text{SBR}} = 2.9 \text{ mJ/cm}^2$). By reduction of the pump power, the Q -switched mode-locked transition was found to occur

at 2-W total output power. When optimized at 20-W output, the pump power could be reduced to give 16-W output without realignment or any loss of stability. At lower-output powers, stability could be reestablished by <1 -mm axial repositioning of the SBR. No damage or deterioration was observed over many (>50) hours of operation. No damage could be induced by chopping the intracavity beam to instigate high-energy Q -switched mode-locked transients. Measurements of the beam quality (see Fig. 9) indicated M^2 values to be 1.12 for the sagittal plane and 1.14 for the tangential plane. The laser output was thus very close to being diffraction limited. Results obtained for the short-format laser suggest that slightly higher output powers of 22–25 W should be possible by optimization of the reflectivity of the output coupling mirror. A single-output beam could readily be achieved by means of replacing the 500-mm ROC mirror situated close to the laser crystal with an appropriate partially transmitting mirror; however, the dual-output beam cavity was used at this time because of limited mirror availability.

To investigate the damage limitations of the SBR, we reduced the spot size on the SBR by a further factor of 2 by replacing the 500-mm ROC mirror with one having a 250-mm ROC. The beam radius on the SBR was therefore reduced to $\sim 67 \mu\text{m} \times 47 \mu\text{m}$. At a summed dual-output average power 20 W ($F_{\text{SBR}} = 9.8 \text{ mJ/cm}^2$), mode-locked operation (at $f = 107 \text{ MHz}$) with a pulse duration

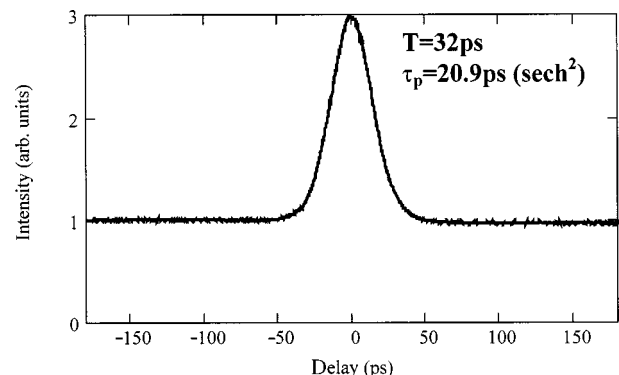


Fig. 8. Intensity autocorrelation of the output pulses from the 90-MHz Nd:YVO₄ laser. The pulse duration was measured as 20.9 ps by assuming a sech^2 pulse shape.

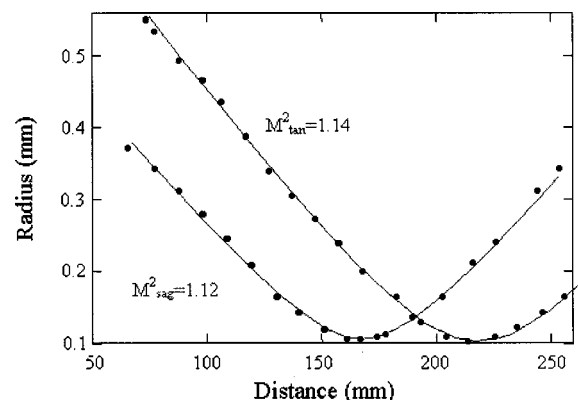


Fig. 9. Beam-quality measurements of the 90-MHz SBR mode-locked Nd:YVO₄ laser.

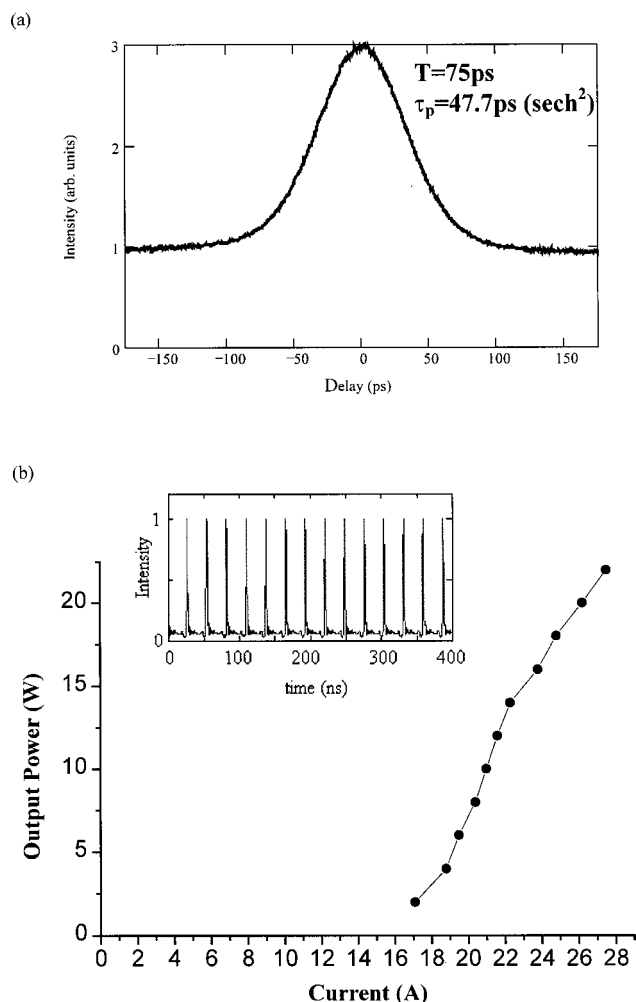


Fig. 10. (a) Intensity autocorrelation trace, and (b) power transfer characteristics obtained from 36-MHz laser. The inset shows the 36-MHz pulse train emitted from the laser.

of ~ 20 – 25 ps could be sustained only for ~ 10 s before catastrophic damage was induced (the sample was then translated to access a new region and thus initiate laser oscillation). The damage occurred in the stable mode-locked regime with no Q switching being evident. This peak power density of 0.53 GW/cm² represents the limiting optical intensity the device can withstand. Before damage occurred, the pulse duration was erratic, which indicates that the most likely candidate instigating the damage process was two-photon absorption.

The results obtained from the 90-MHz laser indicate that operating at 25% of the ultimate damage threshold results in damage-free, robust, laser performance. To further scale the average output power of these lasers, the effects of reduced output coupling and increased spot size on the SBR must be studied. In an attempt to access some information about the laser operation when these parameters were varied, a 1:1 magnification cavity was constructed. Owing to mirror availability, the 1:1 relay mirrors had a ROC of 2 m. At ~ 4.2 m the laser length was therefore very long, and the area of the beam spot on the SBR was four times that for the 90-MHz laser. One of the 2-m ROC mirrors had a reflectivity of 80%, giving a total output coupling of $\sim 36\%$. At ~ 26 -A drive current

to the pump diodes the new laser ($f_{\text{cav}} = 36$ MHz) had an average output power of 20.0 W; at 28 A the output increased to 22.0 W ($F_{\text{SBR}} = 1.1$ mJ/cm²). Again the mode-locked pulse train was very stable with pulse durations measured to be 47.7 ps at 20.0–22.0-W output power (see Fig. 10). The pulse peak power was 12.7 kW, and the pulse energy was 0.61 μ J. Interestingly, and for the first time during our studies into SBR mode-locked neodymium lasers, the laser did not exhibit a Q -switched mode-locked regime at low pump powers. At ~ 0.8 -W output (~ 2.2 -W intracavity) power the laser intermittently produced a mode-locked pulse train; therefore this point was defined as the threshold power for the onset of passive mode locking (see Fig. 11). At 1-W output power the laser produced a stable mode-locked output with no drop-outs. Since the illuminated area on the SBR was 1.6×10^{-3} cm², the power density required for initiating mode locking was 1.56 kW/cm² ($F_{\text{SBR}} = 39$ μ J/cm²).

The long (~ 50 ps) pulse durations obtained from the 36-MHz laser reflected the low power density incident on the SBR. As with the 90-MHz laser, the pulse duration should reduce with increased intracavity power, at least until some limiting pulse duration (~ 20 ps) is reached. The pulse duration should also reduce with the introduction of greater saturable absorption. Temperature tuning can be used to optimize the overlap of the SBR absorp-

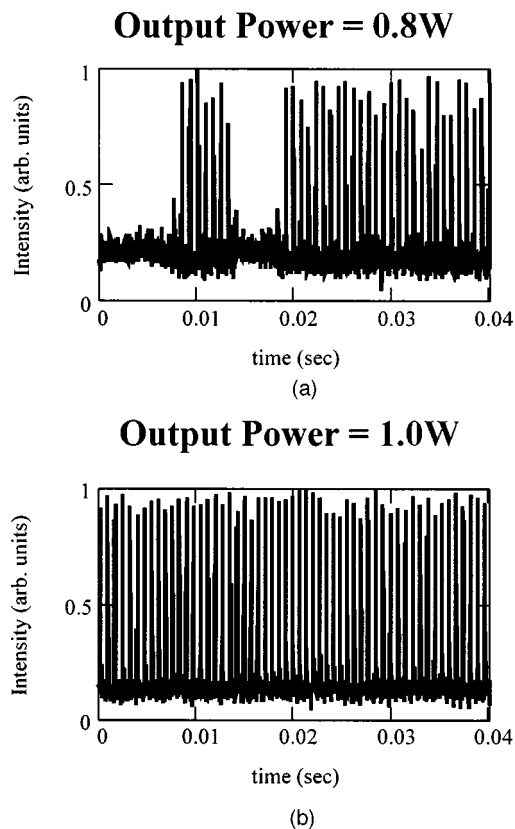


Fig. 11. Onset of SBR mode locking in the long 36-MHz Nd:YVO₄ laser cavity. The intermittent mode-locking and cw oscillation indicate that (a) is close to the threshold conditions for SBR mode locking. In (b) the laser produces only a mode-locked output. Note that because of aliasing on the digital oscilloscope, the figures do not show individual pulses; however, the mode-locked and cw states are clearly defined.

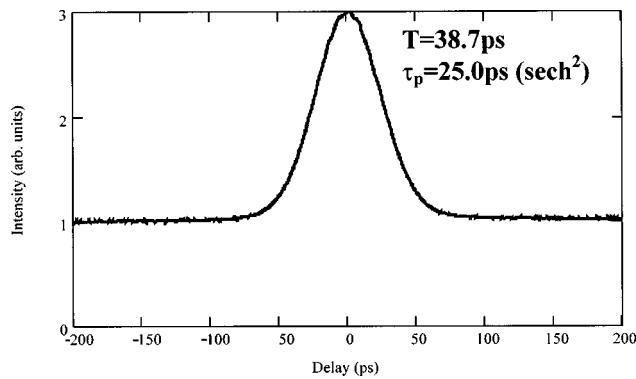


Fig. 12. Intensity autocorrelation of the output pulses from the 36-MHz multibounce SBR mode-locked Nd:YVO₄ laser.

tion resonance with the laser wavelength to increase the saturable absorption. Alternatively, SBR samples that have QW's with increased indium content can be used to shift the absorption to longer wavelengths. DQW SBR samples with 22%, 23%, and 24% indium concentration were used in conjunction with the 36-MHz cavity configuration. The measured resultant pulse durations at an average output power level of 20 W were 47, 36, and 30 ps, respectively. The peak pulse power was therefore increased because of the reduction in the pulse duration to 18.6 kW. Wafers with higher indium concentrations were not available; however, strain relaxation would become more of an issue for concentrations of 25% and greater. To introduce yet higher absorption into the cavity, a second 24% indium DQW SBR was used to fold the intracavity beam onto the SBR. The second SBR sample was placed close to the original sample; therefore, owing to the large (2-m) ROC of the focusing mirror, the beam radius on both samples was approximately the same. For this, the multibounce case, the pulse duration reduced yet further to 25 ps (as shown in Fig. 12), and so the peak power was increased to >24 kW.

Although considerable research is still necessary, these results indicate that power scaling to considerably higher average power levels should be possible and is not limited by damage to the SBR device. To produce optimally short pulses, the power density incident on the SBR should be kept at a reasonable fraction of the damage threshold; however, as the intracavity power increases, the spot size must also be increased. In this manner the average output power can potentially be scaled without limit. The real problem that exists for lasers with output powers of many tens of, or a few hundred, watts is in imposing sufficient mode control to instigate single-transverse-mode operation. The potential for both high beam quality and high average power operation was recently demonstrated in a diode-pumped Nd:YAG laser for which TEM₀₀ operation was obtained with output powers of more than 200 W.¹⁸ If SBR mode-locked lasers can be developed at these very high power levels, greater consideration must be given to the temperature control of the SBR. For large spot sizes the heat flow becomes progressively more one dimensional, and proper heat sinking will be necessary for maintaining the appropriate device temperature and hence modulation depth.

7. CONCLUSIONS

A double InGaAs quantum-well (QW) saturable Bragg reflector (SBR) has been developed for use in high-average-power neodymium-doped lasers operating near 1 μm . By use of a lower indium concentration, the strain-thickness product for each QW is further away from the critical value where strain relaxation occurs and as such should have better morphology. However, owing to the reduced absorption present at the laser wavelength, two QW's were required for good mode-locked performance, and so the total strain was again increased. When three thin GaAsP layers are incorporated, the strain of the total structure can be compensated. The resultant strain-balanced device features both appropriate saturable absorption for mode locking and low background unsaturable losses. The new devices were initially assessed by comparison to strained single-QW (SQW) SBR's, and in this way it was estimated that the unsaturable loss of the strain-balanced SBR's was reduced by a factor of at least 2–3.

A methodology for obtaining stable, thermal-lens-invariant, single-transverse-mode operation of intermediate-power (tens of watts) neodymium lasers was coupled to the lens relay approach, to extend the cavity length and introduce spot size control, in the design of a diode-laser-pumped Nd:YVO₄ laser. When the new SBR was incorporated within the side-pumped Nd:YVO₄ laser, mode-locked pulses of 21-ps duration were obtained for average output powers of 20 W and peak pulse powers of 10.6 kW. By extension of the cavity to produce mode-locked pulses at a repetition frequency of 36 MHz, the fundamental limitations on this power scaling approach were investigated with the conclusion that average output powers well over 100 W should be possible. Such output power levels will not be limited by the strain-balanced SBR but more with the problems associated with transverse-mode control of the high-power level.

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REFERENCES AND NOTES

1. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chui, J. F. Ferguson, and M. T. Asom, "Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber," *Opt. Lett.* **17**, 505–507 (1992).
2. U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE J. Sel. Top. Quantum Electron.* **2**, 435–451 (1996), and references therein.
3. S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, "Mode-locking ultrafast solid-state lasers with saturable Bragg reflectors," *IEEE J. Sel. Top. Quantum Electron.* **2**, 454–464 (1996), and references therein.
4. J. D. Kafka, M. L. Watts, and J. W. Pieterse, "Synchronously pumped optical parametric oscillators with LiB₃O₅," *J. Opt. Soc. Am. B* **12**, 2147–2157 (1995).
5. B. Ruffing, A. Nebel, and R. Wallenstein, "A 20-W KTA-OPO synchronously pumped by a cw mode-locked Nd:YVO₄ oscillator-amplifier system," in *Lasers and Electro-Optics*,

- Vol. II of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper CWB2.
6. J. Aus der Au, S. F. Schaer, R. Paschotta, C. Honninger, and U. Keller, "High-power diode-pumped passively mode-locked Yb:YAG lasers," *Opt. Lett.* **24**, 1281–1283 (1999).
 7. G. J. Spuhler, R. Paschotta, U. Keller, M. Moser, M. J. P. Dymott, D. Kopf, J. Meyer, K. J. Weingarten, J. D. Kmetec, J. Alexander, and G. Truong, "Diode-pumped passively mode-locked Nd:YAG laser with 10-W average power in a diffraction-limited beam," *Opt. Lett.* **24**, 528–530 (1999).
 8. C. J. Howle, A. I. Ferguson, S. T. Lee, D. Burns, and M. D. Dawson, "A high power SBR mode-locked Nd:YLF laser," in *European Conference on Lasers and Electro-Optics*, Vol. 6 of 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998), paper CtuE3; T. Graf, A. I. Ferguson, E. Bente, D. Burns, and M. D. Dawson, "Multi-watt Nd:YVO₄ laser, mode locked by a saturable Bragg reflector and side pumped by a diode laser bar," *Opt. Commun.* **159**, 84–87 (1999).
 9. C. A. Wang and H. K. Choi, "Organometallic vapor phase epitaxy of high performance strained-layer InGaAs-AlGaAs diode lasers," *IEEE J. Quantum Electron.* **27**, 681–686 (1991).
 10. R. D. Dupuis and P. D. Dapkus, "Room-temperature operation of Ga_(1-x)Al_xAs/GaAs double-heterostructure lasers grown by metalorganic chemical vapor phase deposition," *Appl. Phys. Lett.* **31**, 466–468 (1977).
 11. J. W. Matthews and A. E. Blakeslee, "Defects in epitaxial multilayers. III. Preparation of almost perfect multilayers," *J. Cryst. Growth* **32**, 265–273 (1976).
 12. R. People and J. C. Bean, "Calculation of critical layer thickness versus lattice mismatch for Ge_xSi_{1-x}/Si strained-layer heterostructures," *Appl. Phys. Lett.* **47**, 322–324 (1985).
 13. L. R. Brovelli, U. Keller, and T. H. Chiu, "Design and operation of antiresonant Fabry-Perot saturable absorbers for mode-locked solid-state lasers," *J. Opt. Soc. Am. B* **12**, 311–322 (1995); C. Honninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, "Q-switching stability limits of continuous-wave passive mode locking," *J. Opt. Soc. Am. B* **16**, 46–56 (1999).
 14. C. Ellmers, M. R. Hofmann, D. Karaiskaj, S. Leu, W. Stolz, W. W. Ruhle, and M. Hilpert, "Optically pumped (GaIn)As/Ga(PAs) vertical-cavity surface emitting lasers with optimized dynamics," *Appl. Phys. Lett.* **74**, 1367–1369 (1999).
 15. $\pm 2\%$ for nonrotated MOCVD growth.
 16. V. Magni, "Resonators for solid-state lasers with large-volume fundamental mode and high alignment stability," *Appl. Opt.* **25**, 107–117 (1986).
 17. V. Magni, "Multielement stable resonators containing a variable lens," *J. Opt. Soc. Am. A* **4**, 1962–1969 (1987).
 18. Y. Hirano, Y. Koyata, S. Yamamoto, K. Kasahara, and T. Tajime, "208-W TEM₀₀ operation of a diode-dumped Nd:YAG rod laser," *Opt. Lett.* **24**, 679–681 (1999).