Mode locking of external-cavity semiconductor lasers with saturable Bragg reflectors

J. L. Shen

Department of Physics, Chung Yuan Christian University, Chung-Li 32023, Taiwan

T. Jung, S. Murthy, T. Chau, and M. C. Wu

Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, California 90095-1594

D. T. K. Tong

Lucent Technologies, Bell Laboratories, Holmdel, New Jersey 07733

Y. H. Lo, C. L. Chua, and Z. H. Zhu

School of Electrical Engineering, Cornell University, Ithaca, New York 14853

Received October 2, 1998; revised manuscript received February 8, 1999

We demonstrate the mode locking of external-cavity semiconductor lasers by using a saturable Bragg reflector as an external reflector. Output pulses of 1.9 ps were generated from the semiconductor lasers without dispersion compensation. By coupling the output to a standard single-mode filter with a length of 35 m to compensate for the linear chirp, we have achieved mode-locked pulse durations as short as 880 fs. © 1999 Optical Society of America [S0740-3224(99)01107-8]

OCIS codes: 140.4050, 230.1480, 140.5960, 320.5520.

Ultrashort optical pulses have broad applications in electro-optic sampling, broadband submillimeter-wave generation, optical computing, and other areas of opto-electronics. Mode-locked semiconductor lasers are compact sources of ultrashort pulses.[1] Passive and hybrid mode locking has been employed to generate subpicosecond pulses in semiconductor lasers. The saturable absorber used in a passive or hybrid mode-locked semiconductor laser needs to satisfy the following requirements: The absorber should saturate faster than the gain medium, and the recovery time of the saturable absorber should be faster than that of the gain medium. Two main kinds of semiconductor saturable absorber were investigated for passive mode locking: proton-bombarded semiconductors and semiconductor quantum wells. The quantum-well absorbers whose absorption saturation is due to the screening of excitons by free carriers are attractive for use in passive mode locking because they are inexpensive and compact, cover a wide wavelength range, and have a fast response time.[2] Recently a low-loss, epitaxially grown semiconductor saturable Bragg reflector (SBR) was demonstrated to be a powerful saturable absorber for passive mode locking.[2–7] The SBR consists of semiconductor quantum wells embedded in a Bragg reflector and functions as a nonlinear mirror for saturable absorption. This design reduces the losses introduced in the cavity, increases the saturation intensity, and raises the damage threshold.[5] Femtosecond pulses have been generated by SBR's in passive solid-state lasers[2–6] and fiber lasers.[7] Although there has been progress in using solid-state lasers with SBR's, semiconductor optical sources have some special advantages. For example, the semiconductor lasers provide the advantages of high quantum efficiency, electrical pumping, and high repetition frequency in the optical communication system. To date, semiconductor lasers combined with SBR's have, however, not been studied to our knowledge. In this paper we report on the generation of short optical pulses in external-cavity mode-locked semiconductor lasers with SBR's. The SBR is shown to be highly effective in broadening the mode-locked spectrum and reducing the pulses width. Mode-locked pulses with 1.9-ps duration were generated without external compensation. By coupling the output light to a 35-m-long single mode fiber (SMF) to compensate for the linear chirp, we achieved optical pulses with durations of 880 fs.

The lasers used in the experiment were buried-heterostructure InGaAs/InGaAsP/InP multiple-quantum-well lasers grown by organometallic vapor phase epitaxy. The multiple-quantum-well active region consisted of five 5-nm-thick InGaAs quantum wells separated by four 22.5-nm-thick InGaAsP barrier layers. The lasing wavelength of the laser was 1.55 μm. The laser was divided into three sections: a 30-μm-long saturable absorber located on one edge of the chip, a 1-mm-long gain section in the center, and another 30-μm-long section on the other edge. The last section was not used in the experiments. Other detailed information on the laser appears in Ref. 8.

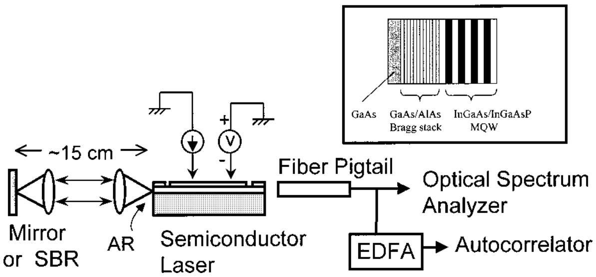

Fig. 1. Schematic of the experimental setup for mode locking with a SBR. Inset, structure of the SBR.

The pulse repetition rate of the mode-locked semiconductor laser was reduced to 1 GHz by coupling of the laser to an external cavity through two lenses, as shown in Fig. 1. A conventional mirror or the SBR was used as the reflector of the external cavity. The facet facing the external cavity was antireflection (AR) coated to less than 1% reflectivity by $Si-SiO_2$ thin films. The structure of the SBR is shown in the inset of Fig. 1. The SBR consisted of a semiconductor Bragg reflector and two sets of 15 InGaAs/InGaAsP strain-compensated multiple quantum wells separated by 80 nm of lattice-matched InGaAsP.[9] To increase the bandwidth of the reflector, we employed 27 pairs of GaAs/AlAs quarter-wave stacks as the Bragg reflector instead of the conventional InGaAsP/InP mirrors. To confirm the suitability of this setup we simulated the reflectivity of 20-pair GaAs/AlAs and InGaAsP/InP Bragg reflectors as a function of wavelength, as shown in Fig. 2. The GaAs/AlAs reflector shows a broader reflection bandwidth and lower loss because it has a large refractive-index. The broader bandwidth is important for short-pulse generation with the SBR in applications at the telecommunication wavelength of 1.55 μm. Because the GaAs/AlAs mirror stack is grown upon a GaAs substrate, we used the wafer-bonding technique to integrate the InP-based quantum wells with the GaAs-based Bragg reflector.[9,10] The output light of the semiconductor laser was coupled into an optical fiber for testing. An optical isolator was employed to prevent disturbance from the reflected light. The output light was then amplified by a diode-pumped erbium-doped fiber amplifier (EDFA) and directed to a noncollinear second-harmonic generation (SHG) autocorrelator with a $LiNbO_3$ crystal and an optical spectrum analyzer.

The threshold current of the antireflection-coated laser was reduced from 95 to 58 mA when it was aligned in the external cavity. When the on-chip saturable absorber was reversed biased, passive mode locking occurred, and optical pulses were observed. The pulse repetition frequency was adjusted to be 1 GHz, corresponding to the round-trip frequency of the external cavity. Stable short optical pulses were achieved by proper adjustment of the cavity alignment, reverse-bias voltage, and forward gain currents. For comparison we used different external reflectors (planar mirror and SBR) to investigate the pulse-shortening effect of the SBR. When a planar mirror was used as the external reflector, the shortest optical pulse width of 5.2 ps was obtained when the gain section and the on-chip saturable absorber were biased to 118 mA and -1.9 V, respectively. The autocorrelation trace is shown in Fig. 3. Under the same bias condition, the pulse width was reduced to 1.9 ps when the planar mirror was replaced by the SBR (Fig. 4). The SBR was involved in the pulse shortening, although mode locking was started by the on-chip saturable absorber. The shorter pulse duration in the latter case indicates that the mode-locking mechanism was dominated by the absorption dynamics of the SBR. The peak wavelength was tunable by adjustment of the position of the focusing lens between the laser and the SBR owing to the chromatic aberrations in the cavity. We found a broadening of the lasing spectrum when the laser was tuned to operate near 1565 nm, which corresponds to the excitonic absorption peak of quantum wells in the SBR. When the wavelength of the laser was moved away from the excitonic absorption of the SBR, the broadening of optical spectrum disappeared and the width of output pulses also increased. This result demonstrates the effectiveness of the SBR in broadening the mode-locked spectral width and shortening the optical pulses.

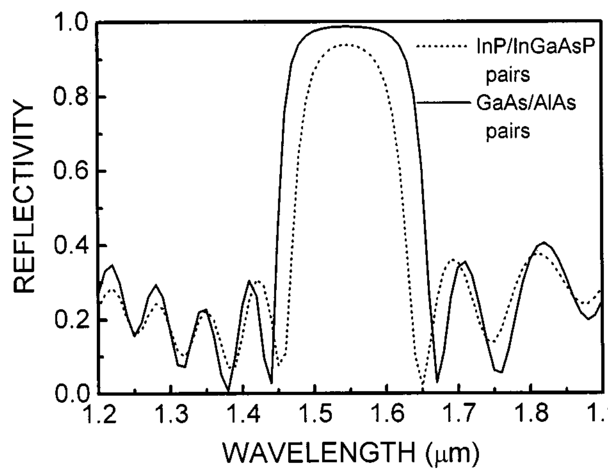

Fig. 2. Reflection spectra of the InP/InGaAsP and GaAs/AlAs Bragg reflectors.

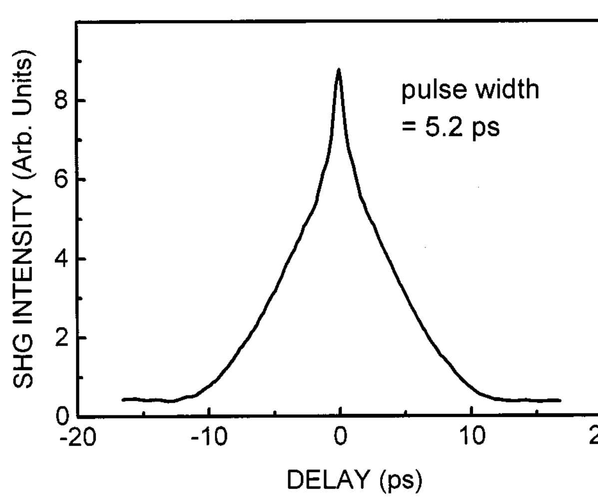

Fig. 3. SHG autocorrelation traces of the output pulses from the mode-locked laser with a planar mirror in the external cavity.

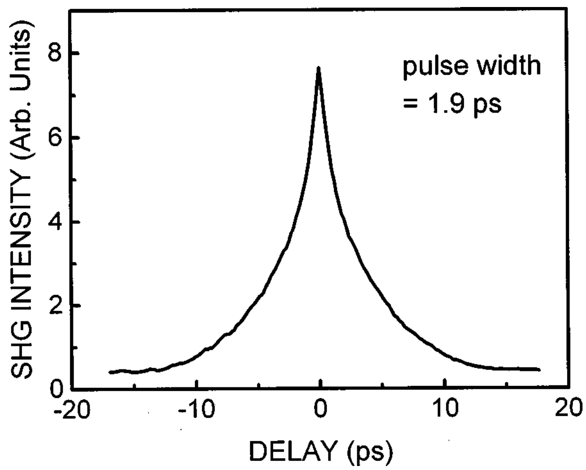

Fig. 4. SHG autocorrelation traces of the output pulses from the mode-locked laser with the SBR in the external cavity.

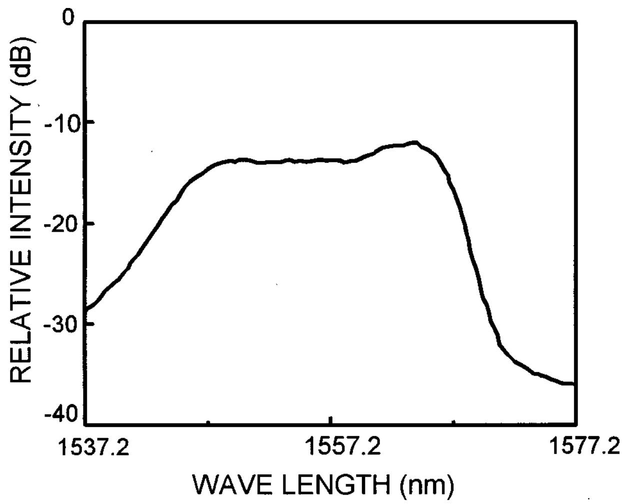

Fig. 5. Time-averaged optical spectrum of the mode-locked laser that corresponds to Fig. 4.

The optical spectrum that corresponds to the 1.9-ps-long pulses is shown in Fig. 5. The spectral width of the mode-locked pulses was approximately 7 nm. The time–bandwidth product of 1.63 was significantly larger than the theoretical value of 0.31 for transform-limited sech^2 pulses. This indicates that the pulses were strongly chirped, which may be due to the saturation of the carrier density in the absorber and the gain section.[11] The pulse width can be shortened by compensation for the frequency chirp. Grating pairs[12,13] and prism pairs[14] are generally used to compensate for linear and the high-order chirp; however, these techniques are quite sensitive to alignment. The linear chirp can be compensated for by dispersive fibers. This scheme does not require any optical alignment and has low loss. In our experiments, a standard SMF with a group velocity dispersion of 16 (ps/km)/nm and a dispersion slope of 0.07 (ps/km)/nm^2 was used to compensate for the first-order chirp. The length of the single-mode fiber was optimized for shortest pulse width. The autocorrelation traces measured after various lengths of the SMF are shown in Fig. 6. The shortest pulses were achieved when the length of SMF was 35 m, corresponding to a total dispersion of 0.64 ps/nm. The autocorrelation trace of the shortest pulses was fitted by a sech^2-pulse shape with a duration of 880 fs, as shown in Fig. 7. The time–bandwidth product was reduced to 0.76 after the compensation. The deviation between theory and experiment in the pedestal indicates the presence of high-order chirps. The high-order chirp can be compensated for by use of two types of optical fibers with different group-velocity dispersions[15] or by the grating-pair method.[12] We also compensated for the output pulses generated by the laser with a planar mirror. The compressed pulses had a pulse width of 3.8 ps (not shown here), much longer than 880 fs.

In conclusion, a passively mode-locked semiconductor laser with an external SBR was investigated for the first time to our knowledge. Optical pulses with durations of 1.9 ps and 880 fs have been achieved without and with linear chirp compensation, respectively. These pulses are significantly shorter than those generated without a SBR. We conclude that use of a SBR is highly effective for generation of subpicosecond pulses in external-cavity mode-locked semiconductor lasers.

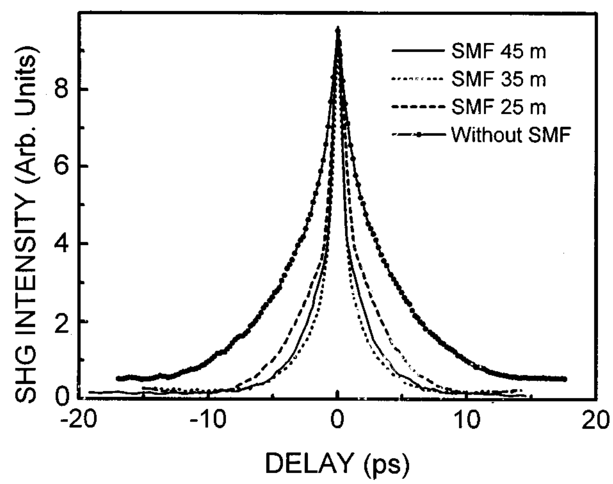

Fig. 6. SHG autocorrelation traces after compression with the SMF at different fiber lengths. The shortest pulse width was found when the SMF length was 35 m.

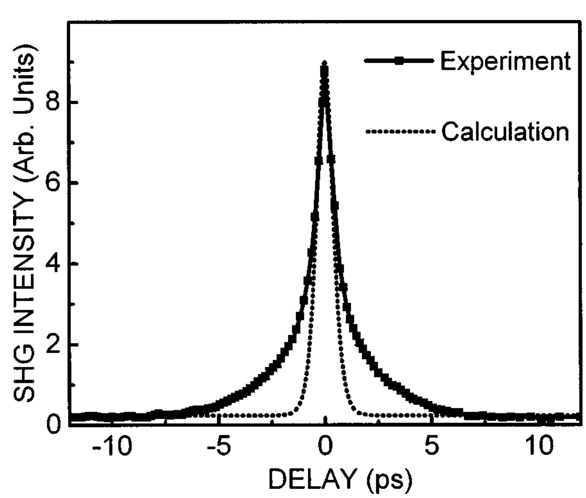

Fig. 7. Shortest pulses are compared with the values calculated with the hyperbolic second waveform.

ACKNOWLEDGMENT

This project is supported by TRW, Inc. The quantum-well lasers were fabricated at AT&T Bell Laboratories.

REFERENCES

1. D. J. Derickson, R. J. Helkey, A. Mar, J. R. Karin, J. G. Wasserbauer, and J. E. Bowers, "Short pulse generation using multisegment mode locked semiconductor lasers," IEEE J. Quantum Electron. **28**, 2186–2202 (1992).
2. L. R. Brovelli, I. D. Jung, D. Kopf, M. Kamp, M. Moser, F. X. Kartner, and U. Keller, "Self-starting soliton mode-locked Ti:sapphire laser using a thin semiconductor saturable absorber," Electron. Lett. **31**, 287–289 (1995).
3. S. Tusda, 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).
4. S. Tusda, W. H. Knox, E. A. de Souza, W. Y. Jan, and J. E. Cunningham, "Low-loss intracavity AlAs/AlGaAs saturable Bragg reflector for femtosecond mode locking in solid-state lasers," Opt. Lett. **20**, 1406–1408 (1996).
5. B. C. Collings, J. B. Stark, S. Tsuda, W. H. Knox, J. E. Cunningham, W. Y. Jan, and R. Pathak, "Saturable Bragg reflector self-starting passive mode locking of a Cr^{4+}:YAG laser pumped with a diode-pumped Nd:YVO_4 laser," Opt. Lett. **21**, 1171–1173 (1996).
6. S. Tusda, W. H. Knox, and S. T. Cundiff, "High efficiency diode pumping of a saturable Bragg reflector-mode-locked Cr:LiSAF femtosecond laser," Appl. Phys. Lett. **69**, 1538–1540 (1996).
7. W. H. Loh, D. Atkinson, P. R. Morkel, M. Hopkinson, A. Rivers, A. J. Seeds, and D. N. Payne, "Passive mode-locked Er3+ fiber laser using a semiconductor nonlinear mirror," IEEE Photonics Technol. Lett. **5**, 35–37 (1993).
8. M. C. Wu, Y. K. Chen, T. Tanbun-Ek, R. A. Logan, M. A. Chin, and G. Raybon, "Transform-limited 1.4 ps optical pulses from a monolithic colliding-pulse-mode-locked quantum well laser," Appl. Phys. Lett. **57**, 759–761 (1990).
9. C. H. Lin, C. L. Chua, Z. H. Zhu, F. E. Ejeckam, T. C. Wu, and Y. H. Lo, "Photopumped long wavelength verticle-cavity surface-emitting lasers using strain-compensated multiple quantum wells," Appl. Phys. Lett. **64**, 3395–3397 (1994).
10. C. L. Chua, Z. H. Zhu, Y. H. Lo, R. Bhat, and M. Hong, "Low-threshold 1.57-μm VCSEL's using strain-compensated quantum wells and oxide/metal backmirror," IEEE Photonics Technol. Lett. **7**, 444–446 (1995).
11. T. Schrans, R. A. Salvatore, S. Sanders, and A. Yariv, "Subpicosecond (320 fs) pulses from cw passively mode-locked external cavity two-section multiquantum well lasers," Electron. Lett. **28**, 1480–1482 (1992).
12. M. Stern, J. P. Heritage, and E. W. Chase, "Grating compensation of third-order fiber dispersion," IEEE J. Quantum Electron. **28**, 2742–2748 (1992).
13. R. A. Salvatore, T. Schrans, and A. Yariv, "Pulse characteristic of passively mode-locked diode lasers," Opt. Lett. **20**, 737–739 (1995).
14. R. L. Fork, C. H. Brito Cruz, P. C. Becker, and C. V. Shank, "Compression of optical pulses to six femtoseconds by using cubic phase compensation," Opt. Lett. **12**, 483–485 (1987).
15. S. Arahira, S. Kutsuzawa, Y. Matsui, and Y. Ogawa, "Higher order chirp compensation of femtosecond mode-locked semiconductor lasers using optical fiber with different group-velocity dispersions," IEEE J. Sel. Top. Quantum Electron. **2**, 480–485 (1996).