Generation of subpicosecond high-power optical pulses from a hybrid mode-locked semiconductor laser

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Ultrashort optical pulses 0.46 psec in duration with over 70 W of peak power are generated from an all-semiconductor laser-diode system. These results represent to our knowledge both the shortest and most-intense optical pulses generated from an all-semiconductor laser system.

In the past, several techniques, such as mode locking and gain switching, have been used to generate picosecond optical pulses from diode lasers with varying degrees of success. Several authors have used degraded semiconductor lasers and multiple-quantum-well (MQW) structures to provide a mechanism for passive mode locking.1-5 The shortest optical pulses, however, have been generated from an actively mode-locked semiconductor laser with a pulse duration of 0.58 psec. The pulses emitted from this system occur in bursts, where the individual pulse separation corresponds to the round-trip time of the laser diode and where the bursts repeat at the external-cavity round-trip time.6

In all the short-pulse generation schemes mentioned above the output power has been low, with typical average powers of the order of a few milliwatts and peak powers approaching 1 W at best. With the advent of high-power semiconductor lasers, experimental results have shown the potential for generating relatively high peak power optical pulses from a semiconductor laser source.7

In this Letter we describe what is to our knowledge the first external-cavity hybrid mode-locked semiconductor laser system that utilizes an external MQW as a saturable absorber. This system produces optical pulses that are initially 5 psec in duration with pulse energies in excess of 100 pJ after amplification through a semiconductor traveling-wave amplifier (TWA). These pulses were compressed to 0.46 psec with over 10 mW of amplified signal power. This translates to over 70 W of peak power. The experimental setup employed is shown in Fig. 1. The picosecond optical pulses were generated from an external-cavity hybrid mode-locked laser. The advantage of utilizing a hybrid mode-locking scheme is that it takes advantage of the stability offered by the actively mode-locked system and also takes advantage of the additional pulse-shortening mechanisms provided by the saturable absorber. The device structure is an angled-stripe TWA that has been described previously.8 The key feature of utilizing this type of structure is that it reduces the residual facet reflectivity of the diode so that single mode-locked optical pulses can be obtained, without the usual multiple coherent spike or multipulse output. In addition, the thin active region (~80 nm) associated with these devices allows them to have a large saturation energy, thus enabling the amplified pulses to contain a large amount of energy, typically 100 pJ.

The mode-locked laser was formed by placing the
The typical average output power from the external cavity was 500 μW. Noticeable satellite pulses were apparent in the autocorrelation traces when the laser was tuned to the operating wavelength of 828 nm. The pulse duration is extremely sensitive to the operation wavelength, thus eliminating the potential for tunability in this laser system. The spectral width of the output pulses under these conditions is typically 2.5 nm [Fig. 2(b)]. From the pulse width measurements and optical spectrum measurements, the time–bandwidth product can be calculated from

\[ \Delta \tau \Delta \lambda c \lambda^{-2} = \text{time–bandwidth product} = \Delta \tau \Delta f. \]  

(1)

From the measurements in Fig. 2, the time–bandwidth product is 5.44, which is approximately 12 times the transform limit assuming Gaussian-shaped pulses. The light from TWA1 contained a total of 50 mW of output power, with 32 mW of amplified signal power and 18 mW of spontaneous emission. The dc bias current to TWA1 in this case was ~300 mA, with an additional 1 W of rf power, where the rf frequency matched the mode-locking frequency and was phase adjusted to yield the maximum gain. The ratio of the amplified signal power to the spontaneous emission power in these experiments was less than the 80% achieved in Ref. 7 owing to the lower repetition rate used here. The amplified signal power of 32 mW translates to 20 W of peak power and also shows that the diode is capable of producing pulses with more than 100 pJ of energy per pulse.

The pulse shape of the hybrid mode-locked pulse and the large time–bandwidth product suggest that there possibly exists a large frequency sweep, or chirp, impressed on the mode-locked pulse. In order to take advantage of this frequency sweep, a standard dual-grating pulse compressor was constructed and employed to compress the mode-locked pulse.\(^9\)

The pulse compressor utilized two blazed gratings, with 1200 lines/mm, and two 15-cm focal length lenses. An adjustable slit was located at the Fourier plane of the telescope inside the compressor, thus permitting it to act as a spectral filter. The compressor was constructed in the double-pass geometry. Owing to the poor diffraction efficiency of the gratings (~50% each), the resultant compressed pulse was subsequently reamplified before it was sent into the autocorrelator. The compressor length was then adjusted to yield the shortest autocorrelation trace after amplification.

The position of the second grating in the pulse compressor was varied in both the positive- and negative-dispersion regimes to achieve the maximum compression ratio. From our experiments the maximum pulse compression occurs by having the grating in the negative-dispersion regime, approximately 7 cm away from the zero-dispersion position. The sign of the chirp in our case is identical to that which was obtained in previous pure passive mode-locking experiments\(^8\) but opposite to that obtained in pure active mode-locking experiments.\(^10\) This shows that the inclusion of the saturable absorber greatly influences the chirping mechanism in the hybrid mode-locking system compared with that of pure active mode locking.

For optimal pulse compression the alignment of the mode-locked oscillator was initially adjusted so that
Fig. 3. (a) Autocorrelation trace of the compressed pulse with an optimized oscillator to yield the shortest compressed pulse. The autocorrelation FWHM is 0.72 psec, which gives a deconvolved pulse width of 0.46 psec assuming a sech² pulse shape. (b) The corresponding spectrally windowed optical spectrum, with a bandwidth of 3.2 nm.

the oscillator operated with the widest possible bandwidth. The bandwidth in this case could be as much as 4 nm. With appropriate spectral windowing, the optical pulses could then be compressed to 0.56 psec in duration. The amplified average output signal power from TWA2 was 6.5 mW, which translates to 38 W of peak power. An additional 6 mW of spontaneous emission power was also present in the output from TWA2. Larger amplified signal powers were not obtainable owing to the low diffraction efficiency of the gratings and the adjustable slit utilized in the pulse compressor, which limited the amount of injected light into TWA2, which was typically on the order of 100 μW. The optimal light injection power for amplification is typically 800 μW to 1 mW.

To overcome this problem, an optimized compressor was constructed from gold-coated gratings (1800 lines/mm). The total loss from this compressor was ~4 dB, compared with the 20-dB loss from the initial compressor used. With this compressor optical pulses could be compressed down to 0.46 psec, with 10 mW of amplified signal power directly after the compressor, thus eliminating the need for a second stage of amplification. The spectral window in the compressor filters out the spontaneous emission, giving only 1 mW of additional spontaneous emission power. Figures 3(a) and 3(b) show the autocorrelation trace and the windowed spectra, respectively, of the optical pulse for this experimental configuration. The pulse after the compressor, with 10 mW of amplified average signal power, gives a peak power of 72 W. These results represent to our knowledge the shortest and most intense optical pulses obtained from an all-semiconductor laser-diode system.

In summary, hybrid mode locking with optical pulse compression and spectral windowing techniques has yielded optical pulses 0.46 psec in duration with peak powers of over 70 W. The peak powers obtained from this type of system may make photonic switching applications possible with a compact laser source.

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