# Tapered semiconductor amplifiers for optical frequency combs in the near infrared

**Flavio C. Cruz,* Matthew C. Stowe, and Jun Ye**

*JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440*

Received December 1, 2005; revised January 17, 2006; accepted January 18, 2006; posted January 31, 2006 (Doc. ID 66390)

A tapered semiconductor amplifier is injection seeded by a femtosecond optical frequency comb at 780 nm from a mode-locked Ti:sapphire laser. Energy gains of more than 17 dB (12 dB) are obtained for 1 mW (20 mW) of average input power when the input pulses are stretched into the picosecond range. A spectral window of supercontinuum light generated in a photonic fiber has also been amplified. Interferometric measurements show sub-Hertz linewidths for a heterodyne beat between the input and amplified comb components, yielding no detectable phase-noise degradation under amplication. These amplifiers can be used to boost the infrared power in *f*-to-2*f* interferometers used to determine the carrier-to-envelope offset frequency, with clear advantages for stabilization of octave-spanning femtosecond lasers and other supercontinuum light sources. © 2006 Optical Society of America

*OCIS codes:* 250.5980, 320.7130, 120.3930.

Tapered semiconductor amplifiers (TSAs) are known to provide large gains ($\geqslant 20$ dB) for near-IR continuous-wave (cw) lasers, converting a few milliwatts of cw radiation to more than 1 W without degradation in linewidth.[1] These amplifiers have been widely used in atomic spectroscopy,[1–3] in laser cooling and trapping,[4] and for increasing the efficiency of nonlinear frequency conversion of cw lasers into the blue and UV regions.[3–5] Amplification of picosecond pulses with semiconductor amplifiers has also been the subject of numerous investigations,[6,7] particularly in connection with optical communications. Semiconductor amplifiers enjoy inherent advantages of compactness, optical integration, and reduced cost. In this Letter we show that TSAs can be used to amplify short pulse trains from a femtosecond frequency comb[8] while preserving the optical phase coherence. To overcome problems related to gain saturation and finite carrier recombination time in semiconductors (hundreds of picoseconds), the pulses need to be prestretched (chirped).[9] These features suggest their use for precise optical time transfer[10–12] over fiber networks. In addition, we have amplified a spectral window of supercontinuum light generated in a photonic fiber, with gains approaching the unsaturated cw gain at low input powers. TSAs can thus aid *f*-to-2*f* interferometers used to measure and stabilize the carrier-to-envelope offset frequency of mode-locked lasers,[8] which can be of particular advantage for phase stabilization of octave-spanning femtosecond lasers[13,14] or other supercontinuum near-IR laser systems that suffer from limited power in the long-wavelength portion of their spectrum.

With its temperature stabilized at 22°C, the TSA[15] delivers an output power of 500 mW at 780 nm for an injected current of 1.5 A. The amplifier has a maximum injection current of 3.0 A, with input and output apertures of 3 and 190 $\mu$m and a length of 2750 $\mu$m. The small input aperture requires careful mode matching, although the circular input mode is not shaped to the elliptical mode of the TSA. The amplifier's performance is tested under both cw and short-pulse injection. A single-frequency diode laser at 780 nm is used as a cw light source. Short pulses are from a mode-locked Ti:sapphire laser, which emits 25 fs pulses at a 100 MHz repetition rate, in a transform-limited bandwidth (BW) of 35 nm (FWHM) centered at 780 nm. We chirped these pulses up to 400 ps by passing them through different lengths of optical fibers.

Figure 1 shows normalized spectra for the Ti:sapphire laser before and after the pulses have passed through a 21 m long fiber, which chirps the pulses to 150 ps and introduces some spectral broadening (BW, 44 nm). Also shown is the spectrum of the corresponding amplified pulse, showing a gain BW of 14 nm. Spectral components outside the amplifier bandwidth are strongly attenuated. In our measurements of gain, pulse shape, spectra, and phase coherence, we also use a 3 nm bandpass filter at 780 nm (Fig. 1) to limit the laser bandwidth within the amplifier bandwidth. Input and output pulse shapes are measured with a fast photodetector (15 ps response time) and a 12 GHz sampling oscilloscope. Amplification of chirped pulses in our TSA differs from chirped-pulse amplification schemes because the amplifier is saturated and its gain bandwidth is smaller than the bandwidth of the pulse to be amplified. Chirped-pulse amplification was recently demonstrated with TSA by chirping of picosecond pulses to several nanoseconds.[9]

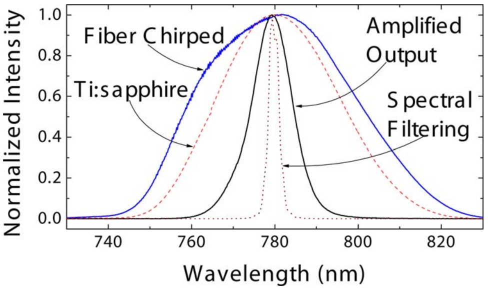

Fig. 1. (Color online) Spectrum of the mode-locked Ti:sapphire laser; spectrum after pulses have passed through 21 m of optical fiber (chirping); laser spectrum after amplification; profile of a 3 nm optical bandpass filter at 780 nm.

0146-9592/06/091337-3/$15.00

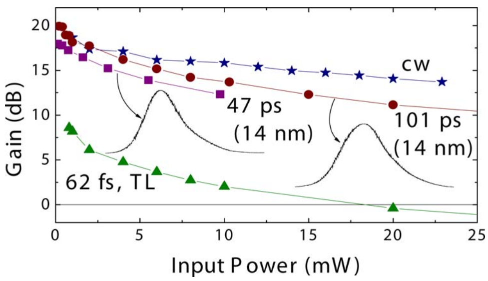

Fig. 2. (Color online) Gain corresponding to cw (⋆) and pulsed injection. Indicated pulse durations are for a TSA BW of 14 nm: 25-fs TL input pulses widened to 62 fs (▲), pulses chirped to 150 ps (44 nm) and then spectrally filtered by the TSA BW to 47 ps (■), pulses chirped to 320 ps (44 nm) and then spectrally filtered to 101 ps (•). Insets, corresponding output pulse shapes (total $x$ scale, 200 ps).

Figure 2 summarizes the results for amplification of cw and short pulses as a function of input power (pulse energy) and pulse duration (chirp). Using the cw laser or spectrally filtered light from the mode-locked laser, we achieve transparency for a bias current of 670 mA. For cw injection and a current of 2.0 A, an unsaturated (small-signal) gain of 20 dB was measured, which was reduced to 14 dB for an input power of 20 mW. An input power of 18 mW (42 mW) was amplified to 500 mW at the output under a bias current of 2.0 A (1.7 A). For short-pulse injection, we measured the average input and output powers. When the laser bandwidth exceeded the amplifier gain bandwidth, the input power was corrected accordingly. From all gain values shown in Fig. 2, the amplified spontaneous emission power (19±1 mW at 2.0 A, without input light) has been subtracted from the output power, which may lead to some underestimation of gain at higher input powers.

TSAs for picosecond pulses have been the subject of numerous investigations.[6,7,16,17] The carrier dynamics is complex; several processes occur on both ultrafast (femtosecond) and slow (nanoseconds and less) time scales. The main limitation in amplifying short pulses arises from the carrier recombination time $\tau_c$ of a few hundred picoseconds.[6] A strong and fast pulse can quickly reduce the carrier density and deplete the gain, which then takes hundreds of picoseconds to recover. This gain variation also causes the changes in index of refraction that are responsible for self-phase modulation.[6] It distorts both the pulse shape and spectrum, which in general become asymmetrical[6] (Figs. 1 and 2). This distortion depends on the amplifier gain, initial chirp, pulse duration, and input energy ($E_{\text{in}}$) compared with saturation energy ($E_{\text{sat}}$).[6] If each pulse reduces the gain considerably, the recombination time will also limit the repetition rate of amplified pulses to a few gigahertz. For ultrashort pulses, another important time scale, of the order of several hundred femtoseconds, associated with nonequilibrium ultrafast carrier heating dynamics is responsible for lower values of $E_{\text{sat}}$,[16] making the gain at increased input power much lower than for longer pulses.

Figure 2 shows the gain for 25 fs transform-limited (TL) pulses and for pulses that have been chirped by fibers to 150 and 320 ps. The TSA BW (14 nm), smaller than the pulse BW, converts these input pulses to 62 fs, 47 ps, and 101 ps, respectively. It is expected that the gain for pulses with duration $\tau_p$ will approach the cw gain if $\tau_p \geqslant \tau_c$ and $E_{\text{in}} \ll E_{\text{sat}}$.[6] We applied the simplified model of Ref. 6, extended to include spontaneous emission[17] and chirped input pulses, in an attempt to account for the results shown in Fig. 2. The asymmetric pulse shapes (Fig. 2, inset) are reproduced, with their durations shorter than the input because of spectral filtering of the amplifier gain BW. Although individual curves in Fig. 2 can be reproduced, assuming reasonable values of $E_{\text{sat}}$ of 60–300 pJ and values of $\tau_c$ of 0.2–1 ns, no single combination of $E_{\text{sat}}$ and $\tau_c$ reproduces all curves. A detailed quantitative analysis of the experimental results would require taking into consideration the amplifier's geometry and gain profile, carrier heating, ultrafast dynamics,[16] and pulse propagation effects.[7,17] In particular, the fast decrease of gain for TL 25 fs pulses is attributed to the smaller values of $E_{\text{sat}}$ that result from the carrier heating dynamics.[16]

Figure 3 shows gain curves for input powers of <1 mW and also when input pulses are spectrally filtered by the 3 nm bandpass filter at 780 nm placed before the amplifier. In this case, for example, pulses that were chirped to 320 ps and then spectrally filtered are shortened to 21 ps. The gain for the 21 ps (3 nm) pulses is expected to be significantly smaller than that of the 101 ps (14 nm) pulses because of the shorter pulse duration. On the other hand, the 21 ps pulses should experience higher gain because their spectrum is near the peak of the amplifier gain (Fig. 1). The combined effects lead to a gain that is somewhat reduced, by 1–3 dB, from that of the 101 ps pulses. Figure 3 also shows the curve that corresponds to amplification of a spectral window (3 nm at 780 nm) of supercontinuum light generated in a microstructure fiber for stabilizing the carrier-to-envelope offset frequency of the comb. For average input powers limited to 300 $\mu$W (within a 3 nm band at 780 nm), we observe gains ranging from 12 to 18 dB. As the input pulse durations are between those of the transform-limited femtosecond pulses and the

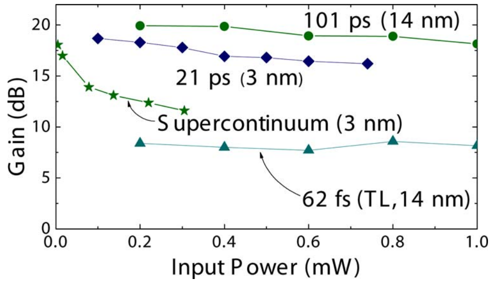

Fig. 3. (Color online) Small-signal gain, with a 3 nm spectral filter inserted before the amplifier. Pulses reaching the amplifier are TL 25 fs (35 nm) and then spectrally filtered to 62 fs (14 nm, ▲); pulses chirped to 320 ps (44 nm) and then spectrally filtered to 101 ps (14 nm, •); pulses chirped to 320 ps (44 nm) and then spectrally filtered to 21 ps (3 nm, ◆); and from the filtered photonic fiber supercontinuum (⋆).

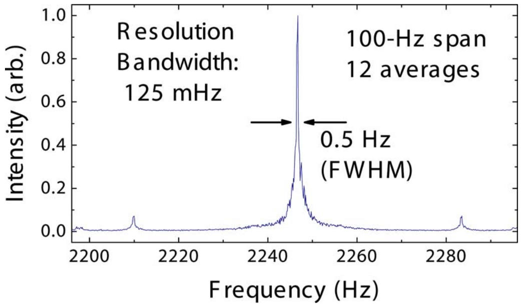

Fig. 4. (Color online) Beat note between input and amplified beams, showing subhertz linewidth.

chirped picosecond pulses discussed above, the faster decrease of gain here can also be attributed to smaller $E_{\mathrm{sat}}$ owing to carrier heating.[16] These gain values demonstrate that a TSA can be useful in amplifying a spectral window of supercontinuum light in the near IR. For example, a commercially available TSA operating at 1.08 $\mu$m (Ref. 15) can be used to boost the power in this region by a factor of 15 dB. This amplification will be beneficial for frequency doubling in a nonlinear crystal used in *f*-to-2*f* spectrometers.

To demonstrate phase coherence between the input and the amplified frequency comb, we performed an optical heterodyne beat experiment, using a Mach–Zehnder interferometer with the tapered amplifier in one arm and an acousto-optic modulator in the other. This enables the optical beat signal to be recorded at a nonzero value, with the interferometer path difference set at zero delay. By mixing the beat signal with another high-quality radio frequency reference, we downconverted the beat signal to an acoustic frequency of a few kilohertz to allow analysis with a high-resolution fast-Fourier-transform analyzer to be performed. Figure 4 shows a beat note recorded in a 100-Hz span on the fast-Fourier-transform analyzer. The beat signals are monitored as a function of the bias current of the TSA, with no changes up to 2.4 A. Spectral features up to a few kilohertz, which correspond to technical noise of electrical and acoustic origins, have also been observed but do not contribute significantly to cause a reduction in the carrier power of the beat. The near spectral-resolution-limited 0.5 Hz linewidth demonstrates that the TSA adds negligible phase noise during amplification and therefore can be used to amplify light from a frequency comb, preserving the phase coherence required for frequency metrology experiments.

In summary, we have demonstrated that a TSA can be used for femtosecond frequency combs if the pulses are considerably chirped. The TSA preserves the phase coherence of the comb at better than the $10^{-15}$ level, which is important for optical frequency measurements and optical time transfer in fiber networks. It can be used to amplify a spectral window of supercontinuum light, with advantages for measuring and stabilizing the carrier-to-envelope offset frequency, with low power in the IR available from sources such as octave-spanning lasers or other low-efficiency supercontinuum systems based on microstructure fibers. We expect that semiconductor amplifiers should be equally useful for frequency combs in the telecom region at 1.55 $\mu$m, where they compete with fiber amplifiers.

This work is supported by the U.S. Office of Naval Research, NASA, and the National Institute of Standards. F. C. Cruz is a 2005 JILA visiting fellow, and he acknowledges support from FAPESP and CNPq–Brazil. F. C. Cruz's e-mail address is flavio@ifi.unicamp.br, and J. Ye's e-mail address is Ye@jila.colorado.edu.

*Also with Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, C. P. 6165, Campinas, S.P. 13083-970, Brazil.

## References

1. J. H. Marquardt, F. C. Cruz, M. Stephens, C. Oates, L. W. Hollberg, J. C. Bergquist, D. F. Welch, and D. Mehuys, in Proc. SPIE **2834**, 34 (1996).
2. G. Ferrari, M. O. Mewes, F. Schreck, and C. Salomon, Opt. Lett. **24**, 151 (1999).
3. C. Zimmermann, V. Vuletic, A. Hemmerich, and T. W. Hänsch, Appl. Phys. Lett. **66**, 2318 (1995).
4. C. Schwedes, E. Peik, J. Von Zanthier, A. Y. Nevsky, and H. Walther, Appl. Phys. B Photophys. Laser Chem. **76**, 143 (2003).
5. D. A. Manoel, D. L. S. Figueira, D. Pereira, and F. C. Cruz, Opt. Eng. (Bellingham) **43**, 1311 (2004).
6. G. P. Agrawal and N. A. Olsson, IEEE J. Quantum Electron. **25**, 2297 (1989).
7. E. Gehrig, D. Woll, M. A. Tremont, A. Robertson, R. Wallenstein, and O. Hess, J. Opt. Soc. Am. B **17**, 1452 (2000).
8. J. Ye and S. T. Cundiff, eds., *Femtosecond Optical Frequency Comb Technology* (Springer-Verlag, 2005).
9. K. Kim, S. Lee, and P. J. Delfyett, Opt. Express **13**, 4600 (2005).
10. J. Ye, J. L. Peng, R. J. Jones, K. W. Holman, J. L. Hall, D. J. Jones, S. A. Diddams, J. Kitching, S. Bize, J. C. Bergquist, L. W. Hollberg, L. Robertsson, and L. S. Ma, J. Opt. Soc. Am. B **20**, 1459 (2003).
11. K. W. Holman, D. J. Jones, D. D. Hudson, and J. Ye, Opt. Lett. **29**, 1554 (2004).
12. K. W. Holman, D. D. Hudson, J. Ye, and D. J. Jones, Opt. Lett. **30**, 1225 (2005).
13. L. Matos, D. Kleppner, O. Kuzucu, T. R. Schibli, J. Kim, E. P. Ippen, and F. X. Kaertner, Opt. Lett. **29**, 1683 (2004).
14. T. M. Fortier, D. J. Jones, and S. T. Cundiff, Opt. Lett. **28**, 2198 (2003).
15. At 780 nm we used TSA model EYP-TPA-0780-00500-3006-CMT03-0000 from EagleYard. TSAs at 1.08 $\mu$m are also available from different companies. Mention of commercial products is for information only; it does not imply NIST recommendation or endorsement, nor does it imply that the products mentioned are necessarily the best available for the purpose.
16. Y. Lai, K. L. Hall, E. P. Ippen, and G. Eisenstein, IEEE Photon. Technol. Lett. **2**, 711 (1990).
17. M. Y. Hong, Y. H. Chang, A. Dienes, J. P. Heritage, and P. J. Delfyett, IEEE J. Quantum Electron. **30**, 1122 (1994).