Tapered semiconductor amplifiers for optical frequency combs in the near infrared

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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 amplification. These amplifiers can be used to boost the infrared power in f-to-2f 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

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Tapered semiconductor amplifiers (TSAs) are known to provide large gains (>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. These amplifiers have been widely used in atomic spectroscopy, in laser cooling and trapping, and for increasing the efficiency of nonlinear frequency conversion of cw lasers into the blue and UV regions. Amplification of picosecond pulses with semiconductor amplifiers has also been the subject of numerous investigations, 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 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). These features suggest their use for precise optical time transfer 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-2f interferometers used to measure and stabilize the carrier-to-envelope offset frequency of mode-locked lasers, which can be of particular advantage for phase stabilization of octave-spanning femtosecond lasers 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 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 μm and a length of 2750 μm. 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, the 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.

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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 fs (■), 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 modelocked laser, we achieve transparency for a bias current of 2.0 A.

As the input pulse durations are between those of the transform-limited femtosecond pulses and the 780 nm continuum, we observe gains ranging from 12 to 18 dB. For average input powers limited to 300 μW (within a 3 nm band at 780 nm), we observe gains ranging from 12 to 18 dB.

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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 $E_{\text{sat}}$. The carrier heating dynamics is responsible for lower values of $E_{\text{sat}}$, 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 heating dynamics is responsible for lower values of $E_{\text{sat}}$. The carrier heating dynamics is responsible for lower values of $E_{\text{sat}}$, making the gain at increased input power much lower than for longer pulses.
chirped picosecond pulses discussed above, the faster decrease of gain here can also be attributed to smaller $E_{\text{sat}}$ owing to carrier heating. 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-$2f$ 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.

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

References

15. At 780 nm we used TSA model EYP-TPA-0780-00050-3006-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.