Optical Differentiation and Multimillijoule ~150-ps Pulse Generation in a Regenerative Amplifier with a Temperature-Tuned Intracavity Volume Bragg Grating

Introduction

Optical differentiators have recently received considerable attention based on their potential application in all-optical signal-processing circuits[1] and optical pulse shaping.[2–4] In Ref. 4 an ultrafast optical differentiator based on long-period fiber grating with subpicosecond temporal resolution was demonstrated. An ultrafast optical differentiator based on an asymmetric Mach–Zehnder interferometer was proposed in Ref. 5. An optical-differentiator operation using a GaAs/AlAs short-period super lattice near an optical absorption band edge was demonstrated in Ref. 6.

Holographic volume Bragg gratings (VBG's) represent a new class of robust, highly efficient, and spectrally selective optical elements that are recorded in photo-thermo-refractive glass.[7] VBG's have spectral and angular dispersions that are higher than any dispersive elements previously used. VBG's are stable at elevated temperatures, have an optical damage threshold similar to that of bulk glass materials, and have high diffraction efficiency and low losses that enable one to use them in laser resonators.

An optical differentiation in a regenerative amplifier (RA) with a temperature-tuned VBG as an intracavity spectral filter is reported for the first time. Using an RA with a VBG as a spectral filter greatly improves optical differentiator performance because of multiple passes through the filter and significant RA gain that increases differentiator efficiency and makes its practical application possible.

One of the appealing applications of an RA in differentiation mode is producing multimillijoule ~150-ps pulses—important for laser–matter interaction studies and laser micromachining. Producing these pulses usually requires a mode-locked oscillator in combination with a regenerative amplifier[8] or a Q-switched microchip laser[9] that requires an additional amplifier because of low, <1-μJ output-pulse energy. In this article a simple and reliable multimillijoule ~150-ps laser system based on an RA operating in differentiation mode with a temperature-tuned VBG as a resonator spectrally selective mirror is demonstrated for the first time.

Experimental Setup

The Nd:YLF diode-pumped RA shown in Fig. 119.22(a) is almost identical to the one described in Ref. 10 except that it has a longer cavity length. The RA has a folded linear cavity with a round-trip time of 21 ns, which makes it possible to amplify pulses as long as 13-ns FWHM in duration. The Nd:YLF active element was oriented for a 1053-nm operational wavelength. It was pumped by a 150-W, fiber-coupled laser diode array (Apollo Instruments, Irvine, CA), which was operated in a pulsed mode, producing 1-ms pump pulses at 805 nm with a 5-Hz repetition rate. The RA intracavity Pockels cell driven by fast electrical circuitry makes it possible to inject and cav-

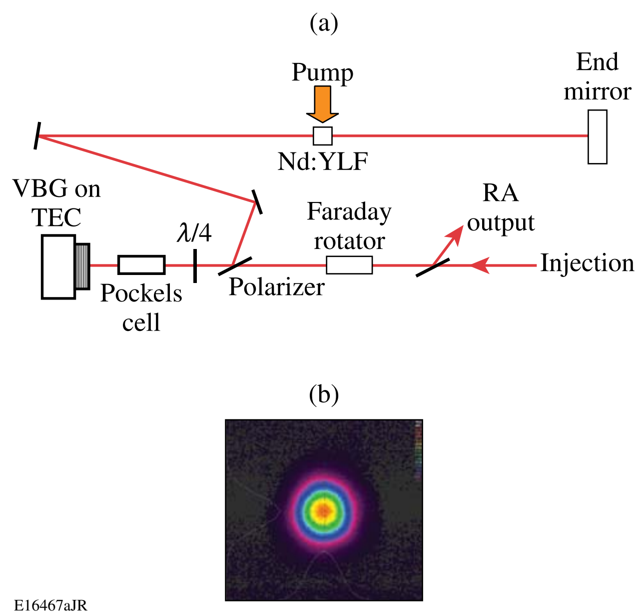

Figure 119.22
(a) A Nd:YLF diode-pumped regenerative amplifier (RA) with a temperature-tuned VBG as a resonator end mirror has been demonstrated. (b) The RA output beam profile corresponds to the TEM_{00} resonator mode. TEC: thermo-electric cooler

ity dump the amplified pulse. The injected pulse was mode matched to the RA resonator and, after a certain number of round-trips, reached its maximum energy and was dumped from the RA cavity. An AR-coated, temperature-tuned VBG (OptiGrate, Orlando, FL) at a 0° angle of incidence was used [Fig. 119.23(a)]. Introducing a VBG as an RA spectrally selective mirror did not alter RA performance, owing to the VBG's high-diffraction efficiency (up to 99.7%). The VBG's high optical quality ensured RA performance in the TEM_{00} resonator mode [Fig. 119.22(b)]. The VBG bandwidth was 240-pm FWHM. The wavelength dependence of the VBG reflectivity is shown in Fig. 119.23(b). The VBG reflectivity maximum can be temperature tuned at an ~10-pm/°C rate. The VBG temperature was maintained with 0.1°C accuracy.

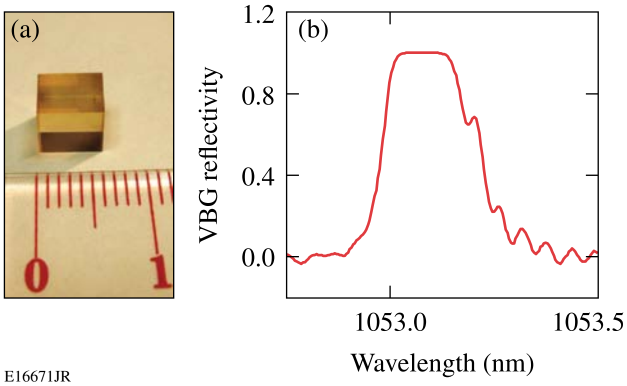

Figure 119.23
(a) VBG's are robust, spectrally selective optical elements that are recorded in photo-thermo-refractive glass. (b) Reflectivity of the VBG used in this experiment was 99.7% with a 240-pm FWHM bandwidth centered at 1053.08 nm.

Optical Differentiation in the RA

The 2.4-ns FWHM precompensated square pulse described in Ref. 11, which is obtained using a system that contains a stabilized single-frequency fiber laser, integrated-optic modulators, and fiber amplifier,[12] is injected into the cavity. If the VBG in the RA is tuned to the maximum of the injected pulse spectrum (shortest RA buildup time), the injected pulse is amplified, maintaining its shape with a slight distortion caused by gain saturation in the RA [see Fig. 119.24(a)]. When the VBG reflectivity is detuned by ~20 pm, positive feedback in the RA resonator is formed for injected pulse broadband components, and the RA performs as an optical differentiator, amplifying only rising and falling edges [Fig. 119.24(b)]. VBG peak-reflectivity detuning by 20 pm provides ~0.3% loss dif-

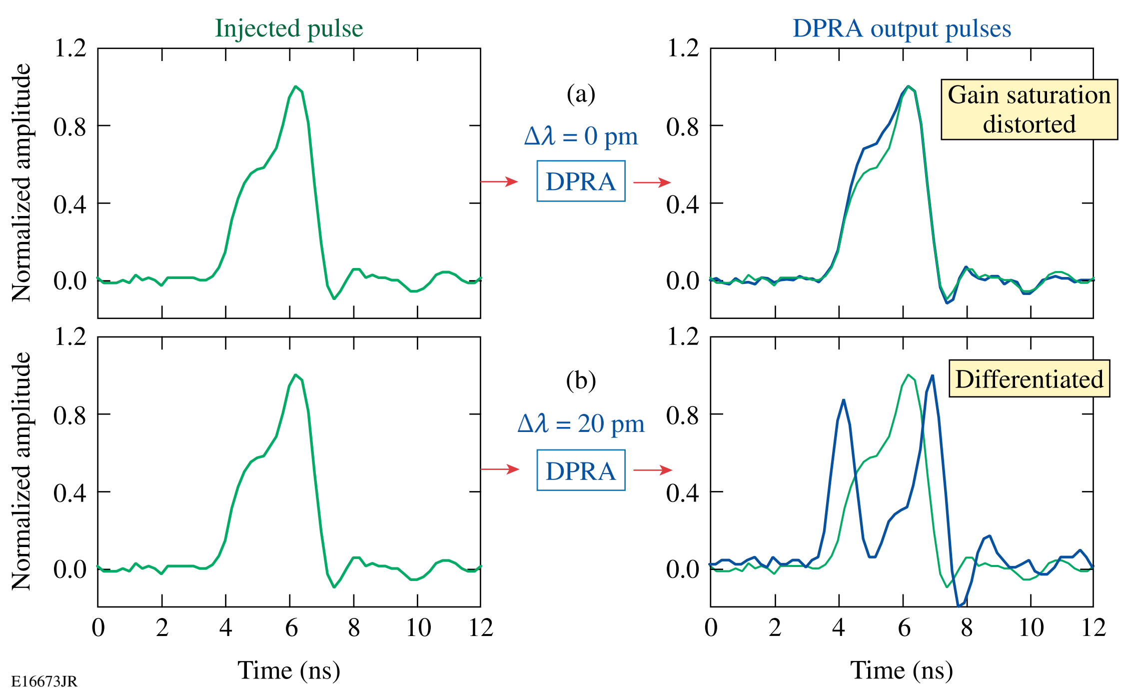

Figure 119.24
(a) The RA shows no peculiarities when VBG is tuned to the injected-pulse central wavelength. (b) The RA works as an optical differentiator when the VBG temperature is detuned from the injected pulse's center wavelength. Note that the gray lines in the right side output pulse are the original normalized injected pulse shape.

ference per round-trip for the injected pulse central wavelength (Fig. 119.25). The total number of round-trips in the RA is 50, which, combined with very high ~10^8 RA gross gain, causes enough discrimination that the center wavelength is not amplified, making the RA an optical differentiator.

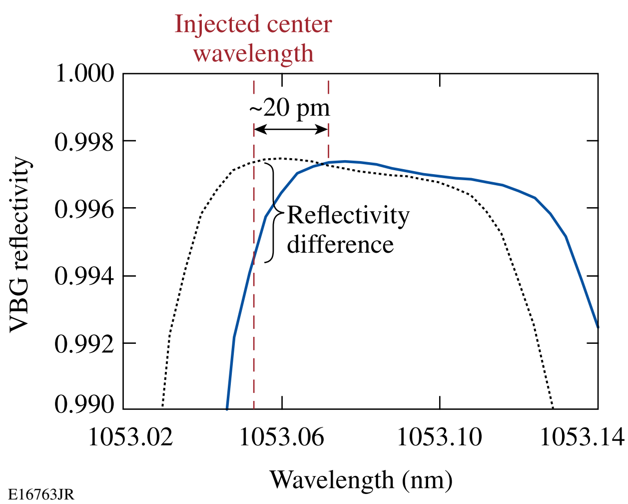

Figure 119.25
Wavelength detuning by 20 pm, which leads to a VBG reflectivity difference of ~0.3% per round-trip, is enough to provide differentiation in the DPRA.

Generation of a Multimillijoule Picosecond Pulse in an RA in Differentiation Mode

One application of an RA as an optical differentiator is generating energetic short pulses without mode-locking. In Ref. 2 it is shown that the generation of an optical pulse with an arbitrary shape may be reduced to the problem of producing an arbitrary spectral filter. An optical differentiator is required as a spectral filter to produce a δ-function pulse. This type of filter with a quarter-wave antireflection coating in reflection mode was proposed in Ref. 2. The efficiency of this device is very low. Using an RA as an optical differentiator provides high efficiency in generating short pulses, owing to significant RA gain and multiple round-trips.

Injecting a step-like pulse is required for producing short pulses out of an RA. The output pulse width is defined by the sharp-edge duration of the injected pulse. A step-like pulse can be produced by using an air breakdown,[2] a fast pulse-shaping system,[12] or a stimulated Brillouin scattering (SBS) mirror.[13] In this article, a system that consisted of a single-frequency Q-switched laser, an SBS mirror, and an RA with a VBG was used. The Q-switched laser produced 4.9-ns-FWHM, 3-mJ TEM_{00} pulses at 1053 nm with a 5-Hz repetition rate. Output pulses were focused into an SBS cell filled with liquid carbon tetrachloride using a 60-mm-focal-length achromat (Fig. 119.26). The 3-ns-FWHM SBS-cell output pulses shown in Fig. 119.26 had a steep 300-ps leading edge, which can be made even shorter (<100 ps) by optimizing SBS cell performance.[13] The SBS cell reflectivity was ~50% when the incoming pulse energy was 2.8 mJ, which was set using a half-wave plate and polarizer combination. After attenuation, an SBS-steepened pulse was launched into a single-mode, polarization-maintaining fiber and injected into the RA with a VBG. The injected pulse energy was 250 nJ.

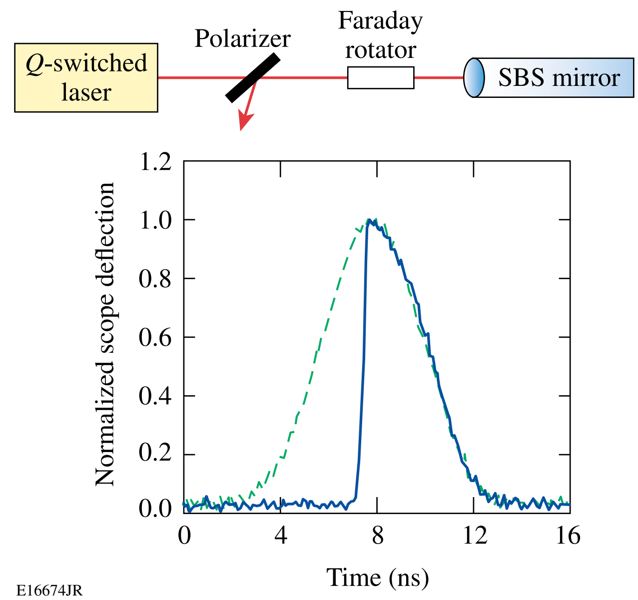

Figure 119.26
A step-like pulse shape with a sharp 300-ps leading edge was produced with an SBS mirror. The dashed line is the input pulse and the solid line is the output pulse from the SBS cell.

When the maximum of the VBG reflectivity curve is tuned to the maximum of the injected pulse spectrum, the RA works in regular regime, producing the amplified up-to-12-mJ pulses shown in Fig. 119.27(a). Pulse shortening from 3-ns to 1.25-ns FWHM occurs as a result of gain saturation in the RA and the sharp leading edge of the injected pulse. When the VBG is detuned from the central wavelength by 25 pm, the RA operates as an optical differentiator and amplifies the leading-edge portion of the injected pulse, producing a 150-ps-FWHM, 12-mJ TEM_{00} pulse at 1053 nm with a 5-Hz repetition rate [Fig. 119.27(b)].

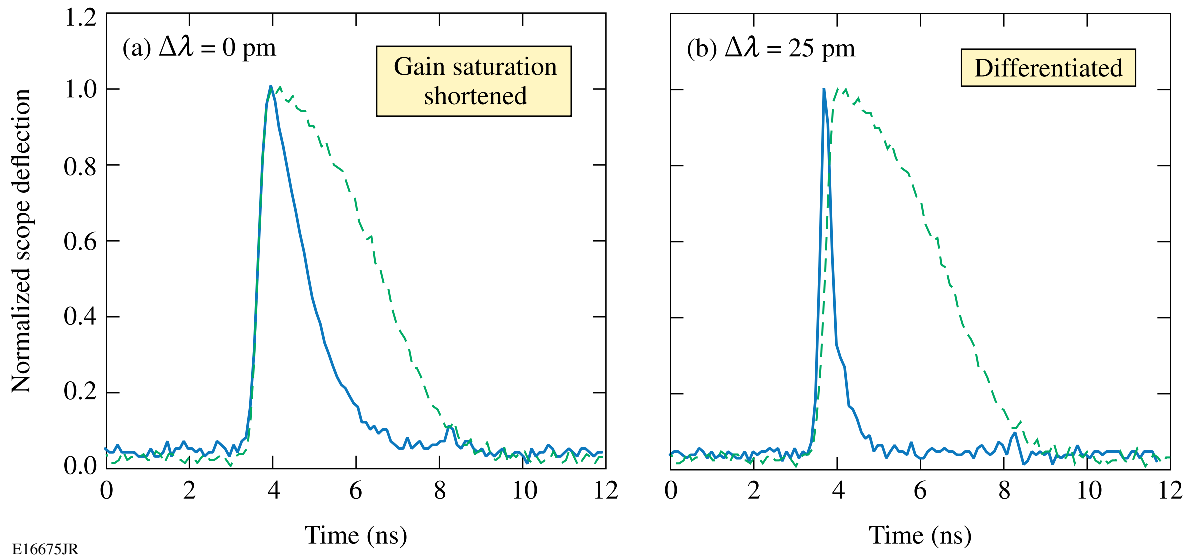

Figure 119.27
(a) The RA with a VBG tuned to the injection central wavelength produced shortened nanosecond pulses as a result of gain saturation of the step-like pulse. (b) When a VBG is temperature detuned, the RA produces 150-ps FWHM multimillijoule pulses after differentiation of a step-like pulse. The dashed line is the input pulse to the RA and the solid line is the RA output pulse shape.

Conclusion

It has been demonstrated for the first time that a regenerative amplifier with a temperature-tuned volume Bragg grating as a spectrally selective resonator mirror works as an optical differentiator when the VBG reflection peak is detuned from the central laser wavelength. A simple, reliable laser system that produces multimillijoule ~150-ps pulses without mode-locking using an RA with a VBG as an optical differentiator has been realized.

ACKNOWLEDGMENT

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