Spectral Filtering in a Diode-Pumped Nd:YLF Regenerative Amplifier Using a Volume Bragg Grating

Introduction

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.[1] VBG's have extremely high spectral and angular dispersions that are higher than any dispersive elements previously used. VBG's are stable at elevated temperatures, have a high optical-damage threshold similar to that of bulk glass materials, and have high diffraction efficiency and low losses, allowing their use in laser resonators.

VBG's are widely used in laser devices for spectrum and beam profile control. Employing VBG's in an external resonator of laser diodes makes it possible to produce high-brightness, near-diffraction–limited beams and coherently combine them.[2] A high-brightness spectral-beam combination of two vertical-external-cavity, surface-emitting lasers has been demonstrated with the aid of a VBG.[3] VBG's have also been used as spectrally selective elements for laser wavelength tuning[4] as well as line narrowing in lasers[5,6] and optical parametric oscillators.[7] Chirped VBG's have been employed for ultrashort-pulse stretching and compression.[8]

Generating high-energy optical pulses in laser amplifiers requires high gain that inherently produces amplified spontaneous emission (ASE) with bandwidths of the order of the amplification bandwidth of the laser system, which can be detrimental to the temporal quality, energy extraction, and stability of laser amplifiers.[9] Amplification of optical pulses usually requires low ASE levels. For example, the temporal contrast of high-energy, short optical pulses amplified by the optical parametric chirped-pulse–amplification (OPCPA) system can be degraded by ASE-induced noise on the pump pulse.[10]

In this article we demonstrate for the first time that employing a VBG as a spectrally selective reflective element in a regenerative amplifier resonator significantly improves the spectral quality of the regenerative amplifier output by suppressing out-of-band amplified spontaneous emission. This spectrally filtered regenerative amplifier should be very beneficial for applications where high spectral quality of pulsed radiation is required, such as pump lasers for high-contrast OPCPA systems.[11]

Experimental Setup

The Nd:YLF diode-pumped regenerative amplifier (DPRA) shown in Fig. 110.45 is identical to the one described in Ref. 12, the only difference being that it has a longer cavity length. It has a folded linear cavity with a round-trip time of 21 ns that allows amplification of pulses as long as 13-ns FWHM in duration. The Nd:YLF active element is oriented for a 1053-nm operational wavelength and is pumped by a 150-W, fiber-coupled laser diode (Apollo Instruments, Irvine, CA), which is operated in a pulsed mode producing a 1-ms pump pulse at 805 nm with a 5-Hz repetition rate. The DPRA intracavity Pockels cell driven by fast electrical circuitry allows the injection and cavity dumping of the amplified pulse. The injected pulse is mode matched to the DPRA resonator and, after a certain number of round-trips, reaches its maximum energy and is dumped from the DPRA cavity (inset in Fig. 110.45). Two DPRA resonator configurations have been compared: (1) with a flat end mirror having 99.9% reflectivity and (2) with a combination of AR-coated VBG (OptiGrate, Orlando, FL) having 99.4% diffraction efficiency and the same flat end mirror. The VBG has a bandwidth of 230 pm (FWHM) centered at ~1053 nm with an ~7° angle of incidence.

Spectral filtering in a regenerative amplifier cavity benefits from the large number of passes on the filtering element. Assuming a single-pass filtering spectral transmission $T(\omega)$, the spectral filter after N round-trips in the cavity is $T(\omega)^N$, or $T(\omega)^{2N}$ if the filter is seen twice per round-trip, which is the case in this implementation. Figure 110.46(a) displays the spectral reflection of a Gaussian filter with a 230-pm (FWHM) bandwidth centered at 1053 nm and the spectral reflection after 50 round-trips in a cavity with two passes on the filter per round-trip. The effective filtering function has a bandwidth of 23 pm (FWHM). Filtering of the ASE can be performed as long as the bandwidth reduction in the amplifier does not degrade the temporal pulse shape of the output pulse. Figure 110.46(b)

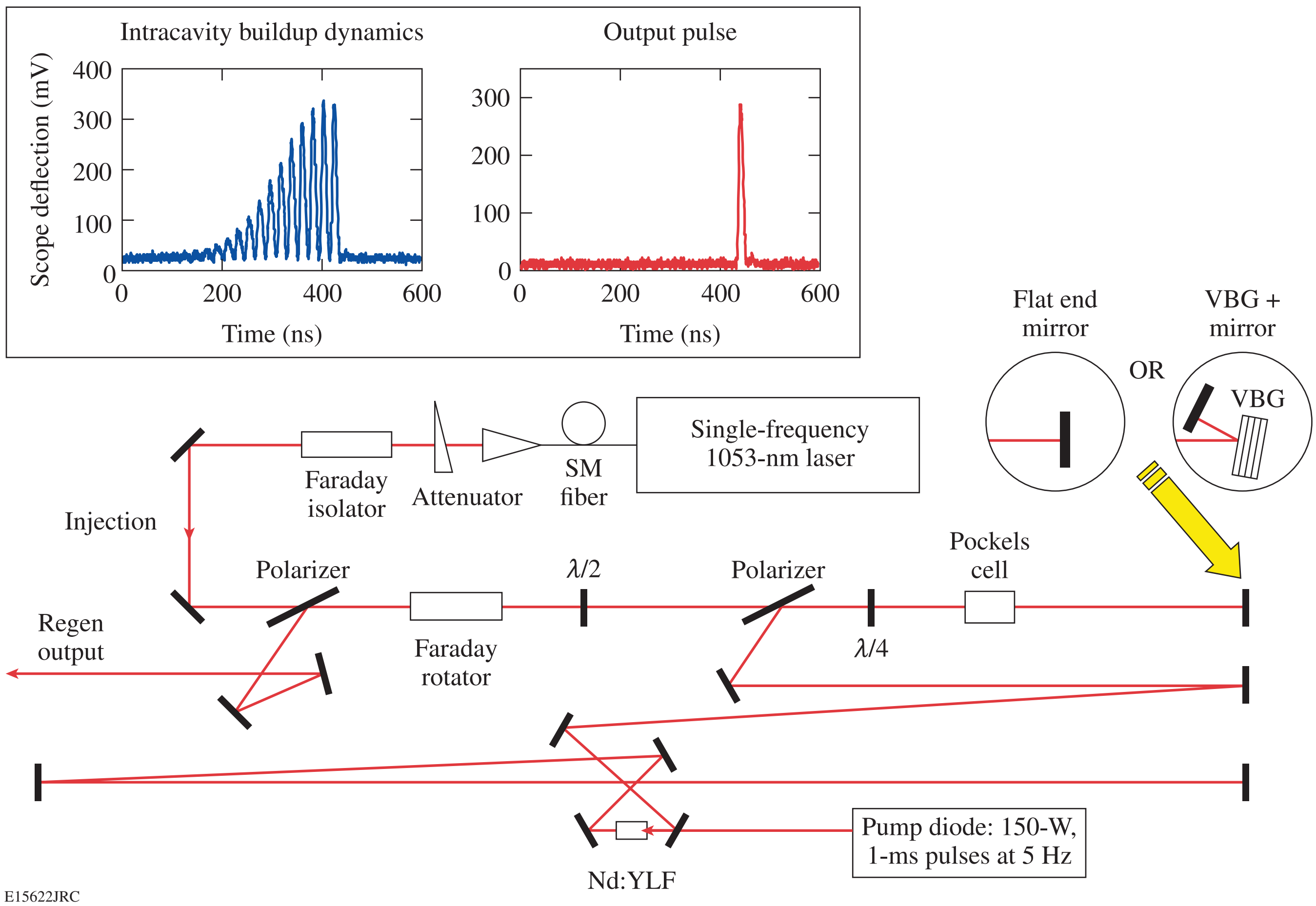

Figure 110.45
A volume Bragg grating (VBG) is used in a folded-linear-cavity regenerative amplifier as one of the mirrors for spectral filtering. DPRA cavity dumping occurs when intracavity buildup reaches its maximum (inset).

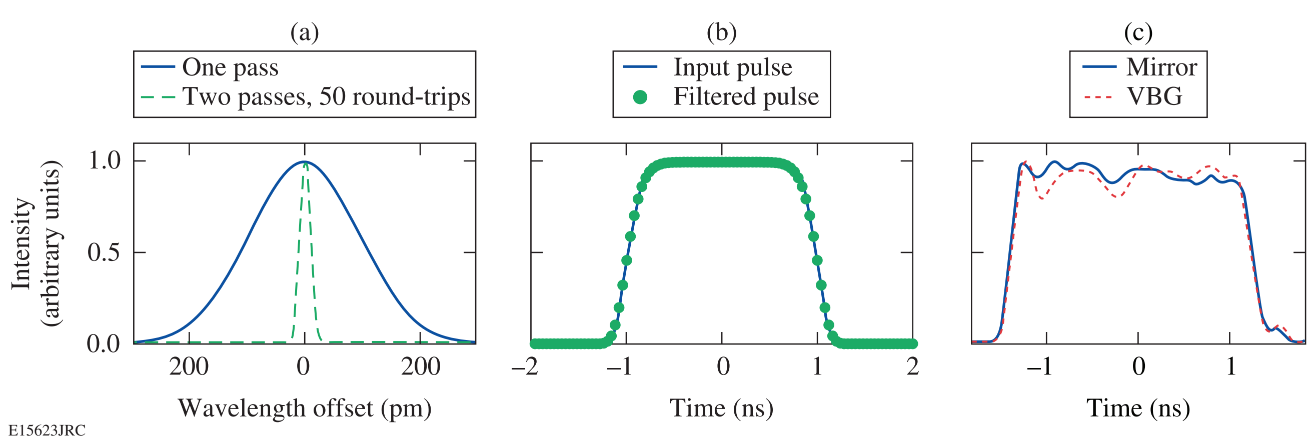

Figure 110.46
(a) VBG with a Gaussian filter function using a 230-pm FWHM, one-pass bandwidth (solid line) produces a filter function with an effective bandwidth of 23-pm FWHM after 50 round-trips in the DPRA with a VBG two-pass configuration (dashed line); (b) 2-ns-FWHM, super-Gaussian pulse before (solid line) and after (white circles) bandwidth narrowing using a 23-pm-FWHM filter (simulation); (c) measured 2.4-ns-FWHM pulse shape after the DPRA with further amplification and doubling for the DPRA with mirror (solid line) and VBG (dotted line).

shows a 2-ns (FWHM), 20th-order super-Gaussian pulse before and after filtering by a 23-pm (at –3-dB level) filtering function. The choice of the 2-ns-FWHM pulse duration corresponds to the typical pulse widths used to pump OPCPA systems.[11] In this simulation, no significant change in the temporal intensity is observed, showing that an even narrower filter could be used. While different round-trips in the cavity correspond to a different effective bandwidth of the filter, ASE is expected mostly from the source seeding the regenerative amplifier and the first few round-trips in the amplifier (when the pulse energy is low), which correspond to the narrowest effective filtering function. Figure 110.46(c) displays the pulse shape measured after amplification in the DPRA and a four-pass ring power amplifier and after second-harmonic generation, for use as the pump pulse in an OPCPA system. No significant change in the output square pulse, including the fast rising and falling edges, is observed when the mirror in the DPRA is replaced with the VBG + mirror combination.

In our experiment the DPRA is injected with a 13-ns-FWHM, Gaussian-like pulse that is sliced out of a 150-ns-FWHM pulse produced by a diode-pumped, single-frequency, Q-switched Nd:YLF laser.[13] The bandwidth of this pulse is obviously narrower than that of the 2-ns-FWHM, super-Gaussian pulse; therefore, no output-pulse distortion due to VBG spectral filtering is expected. The DPRA output energy, beam profile, and spectra have been recorded for both DPRA resonator configurations (with a mirror and a VBG + mirror combination).

Experimental Results and Discussion

The beam profiles shown in Fig. 110.47 correspond to the TEM_{00} mode for both DPRA configurations (mirror and VBG). These beam profiles have been taken at a DPRA operational output-pulse energy of 4 mJ.

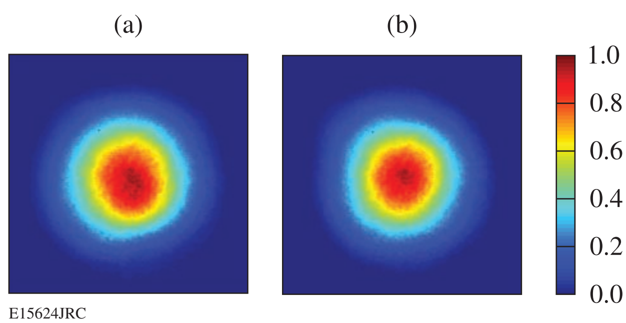

Figure 110.47
Output beam profile corresponds to TEM_{00} mode for both DPRA configurations with (a) a mirror and (b) VBG. DPRA output energy is 4 mJ.

The maximum energy produced by the DPRA with a mirror is 18 mJ. After introducing the VBG into the DPRA cavity, the maximum output energy drops to 14 mJ, which is consistent with introducing ~1.2% of additional losses per round-trip by VBG with 99.4% diffraction efficiency. The output-beam profile corresponds to a TEM_{00} mode over the whole range of output energy when using the VBG.

We recorded an output spectra using an ANDO AQ6317B (Yokogawa Corp. of America, GA) optical spectrum analyzer (OSA) for an injected DPRA and a DPRA without injection with the same number of round-trips (21). In each case the pump diode current has been adjusted to achieve cavity dumping at the maximum of the intracavity pulse-buildup dynamics. An unseeded DPRA with a mirror produces the gain-narrowed ASE spectrum shown in Fig. 110.48 (solid line) with an ASE

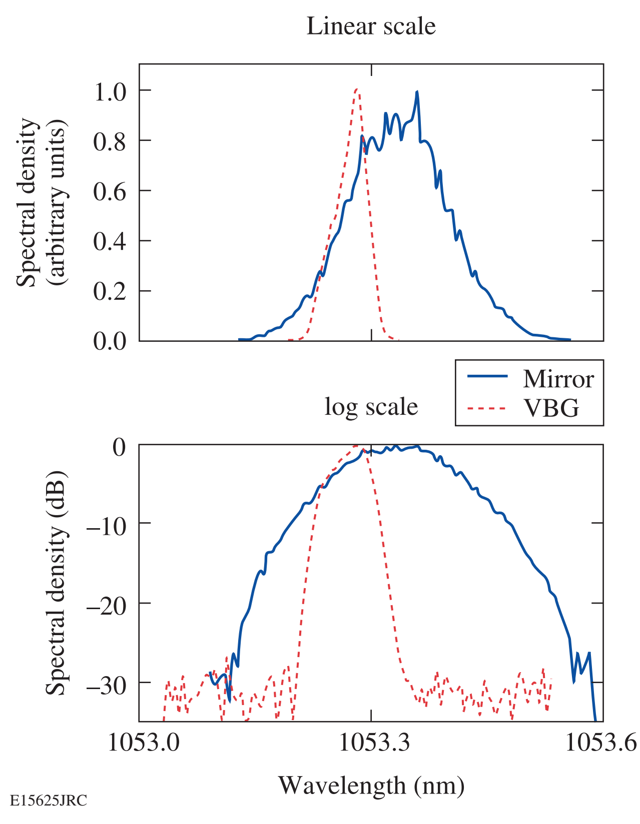

Figure 110.48
Output spectra for the DPRA without injection: the DPRA with a mirror produces a gain-narrowed ASE spectrum with 150-pm FWHM (solid line); the DPRA with the VBG spectrum is narrowed to 43-pm FWHM (dashed line). In the latter case, the spectrum width and shape are defined by the common action of the VBG reflection curve and Nd:YLF gain profile. In both cases DPRA performance has been optimized for cavity dumping after 21 cavity roundtrips.

bandwidth of 150 pm (FWHM). In contrast, the unseeded DPRA using the VBG shown in Fig. 110.48 (dashed line) provides a much narrower spectrum with a width (43-pm FWHM) and shape defined by the common action of the VBG reflection curve and Nd:YLF gain profile. The position of the output spectrum is defined by the VBG angular alignment. The VBG in the DPRA cavity is aligned using an injection laser in cw mode as an alignment beam, i.e., the VBG position provides the best DPRA cavity alignment (maximum VBG reflectivity) for the wavelength that is going to be injected. This injection wavelength is not exactly at the peak of the DPRA gain curve, leading to the asymmetric spectrum shape when using the VBG in a DPRA without injection.

Observing the VBG spectral-filtering effect is limited by an instrument spectral resolution and dynamic range of 20 pm and 40 dB, respectively. We have simulated the DPRA spectral behavior as it will be seen by the OSA to determine experimental conditions for reliable observation of the VBG spectral-filtering effect. Our simulations show that DPRA injection energy must be about equal to ASE energy. The injected pulse energy in this case is ~0.0025 pJ, which corresponds to a gross gain of greater than 10^{12}. The simulated output spectrum of the DPRA with the mirror is shown in Fig. 110.49(a); the simulated output spectrum consists of an injected line on top of an ASE pedestal, which is reliably recorded by the OSA. The measured output spectra are shown in Fig. 110.49(b) and agree very well with the simulated results. The number of round-trips for both simulated and experimental results is 21. In the DPRA with the VBG + mirror combination (even at this very low injection level), the ASE in the output spectrum [shown in Fig. 110.49(b) (dashed line)] is suppressed to the instrument's 40-dB dynamic range. The OSA spectral resolution does not allow us to make the spectra comparison at higher levels of DPRA injection; however, it is obvious that spectral contrast will be even better when the injection level is increased due to domination of the injected pulse over ASE even on initial cavity round-trips.

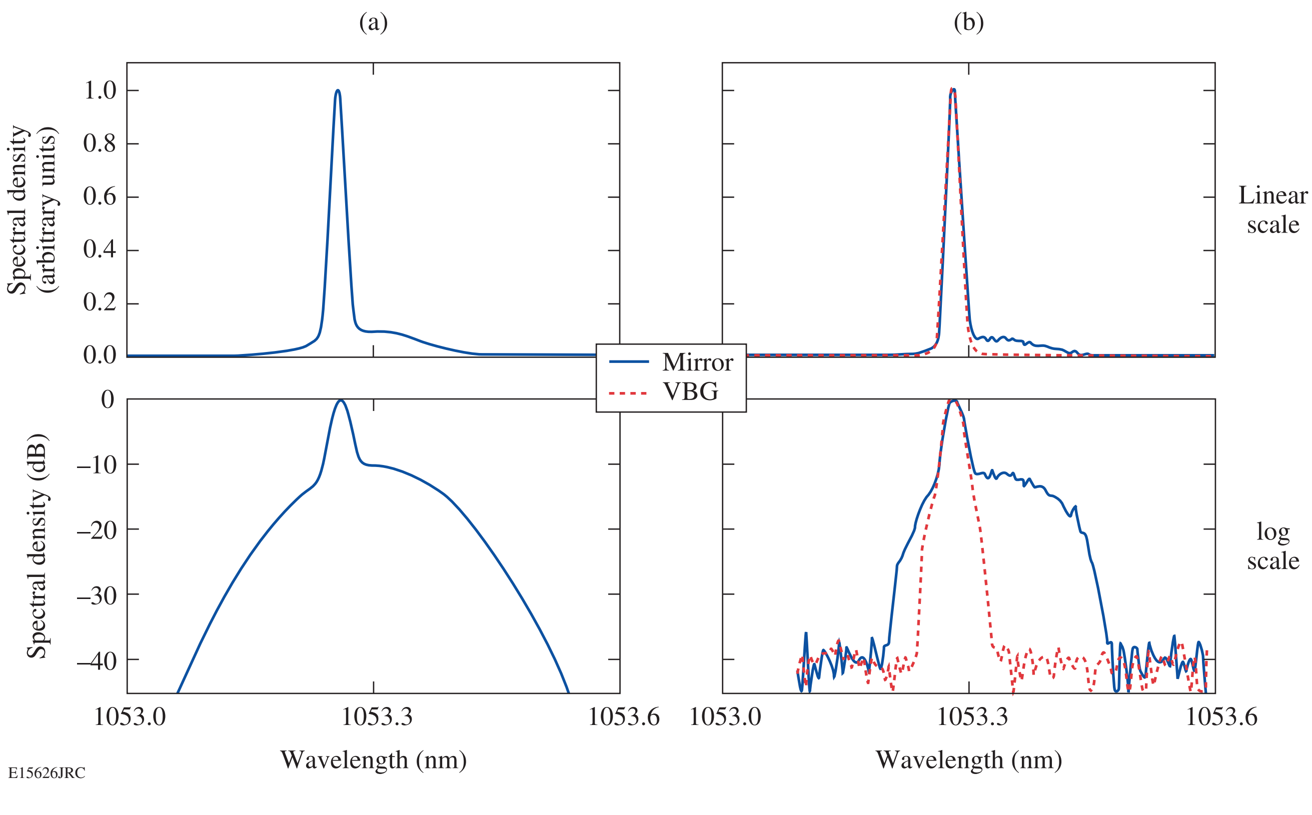

Figure 110.49
(a) Simulations show that for a reliable OSA recording of ASE filtering effect, the injected energy must be about equal to the DPRA ASE (in this case $E_{ASE} = 0.7\ E_{in}$). (b) Output spectra for the DPRA with injected pulse energy of 0.0025 pJ, comparable to DPRA ASE: with the mirror (solid line) a significant ASE pedestal is observed; with the VBG (dashed line), the spectrum does not show any presence of ASE. The number of round-trips (21) is the same for all cases.

Conclusion

We have demonstrated a VBG spectrally filtered DPRA operation for the first time. Using VBG as the DPRA resonator spectrally selective element allows out-of-band ASE suppression even for a very low DPRA injection level. Using DPRA with VBG spectral filtering can be beneficial in high-energy laser amplifiers.

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