Spectral broadening in ultrafast semiconductor optical amplifiers induced by gain dynamics and self-phase modulation

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We investigate experimentally the self-phase modulation (SPM) induced by gain dynamics on picosecond pulses in semiconductor optical amplifiers whose gain recovery is enhanced by amplified spontaneous emission (ASE). The observed pulse spectra are highly asymmetric at low drive currents but become more symmetric with increasing current, owing to the ASE-induced reduction in the gain-recovery time down to 9 ps. Furthermore, the amount of spectral broadening is shown to saturate with drive current. We show that a variety of spectral-lobe strengths is selectable, while maintaining a nearly constant small-signal gain, a feature desirable for all-optical signal processing applications. © 2010 Optical Society of America

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In future high-speed telecommunication systems, all-optical signal processing techniques promise to play a prominent role to avoid electro-optic conversions that are often costly and create data-flow bottlenecks. Semiconductor optical amplifiers (SOAs) have been widely used to perform a variety of all-optical functions such as wavelength conversion [1], regeneration [2], reshaping [3], and pulse compression [4]. However SOA-based techniques often suffer from a serious limitation: the carrier lifetime in SOAs, which governs how quickly device gain recovers, is typically slower than 100 ps.

Research has been performed to reduce the gain-recovery time of SOAs [5–9]. In particular, a specific technique has led to a class of *commercial* SOAs with gain-recovery times below 10 ps. These new SOAs, to our knowledge, use the ASE to saturate the optical gain and to accelerate the gain-recovery process [8–10]. In this Letter, we investigate the impact of this recovery-time enhancement technique on the spectrum of picosecond pulses broadened through SPM induced by SOA gain dynamics [11]. We demonstrate a remarkable evolution of the central and blue-shifted spectral lobes over a wide range of SOA drive currents over which the small-signal gain is nearly constant. A trade off between spectral broadening and symmetry is inherent to how recovery-speed enhancement is achieved in this class of commercial devices.

Figure 1(a) shows the experimental setup used to study spectral broadening of picosecond pulses inside SOAs. We use gain switching of a multi-quantum-well distributed feedback (DFB) laser to produce optical pulses with the FWHM of 57 ps at a wavelength of 1594.41 nm. The DFB laser module is part of an ILX lightwave mount whose bias-T circuitry accepts rf signals up to 2.5 GHz. The threshold current of the laser was 25 mA at 25°C. To obtain gain-switched pulses, the laser was biased at 14.89 mA and driven with a 1 GHz rf signal with 64.4 mA peak amplitude. Figure 1 shows (b) the shape and (c) the spectrum of the resulting gain-switched pulses. The central frequency $\nu_0 = 188.23$ THz is defined using the first moment of the spectrum. The pulse shape is fitted to a Gaussian function, $P(t) = P_0 \exp(-t^2/\tau_p^2)$, resulting in $\tau_p = 34.2$ ps for a 57 ps pulse. The peak power P_0 of our gain-switched pulses was close to 3 mW. The observed spectrum is asymmetric owing to a negative chirp imposed on the pulse during the gain-switching process. In the notation of [12], we estimate the chirp parameter to be $C = -4.91$.

On the diagnostic end of the experiment setup, an optical bandpass filter with a 3 dB bandwidth of 1 nm was used to reject the out-of-band portion of ASE noise. A 50/50 splitter was employed to send the amplified pulses simultaneously into an optical spectrum analyzer (OSA) with resolution of 0.01 nm and into photodiode with a 22 GHz bandwidth. The tem-

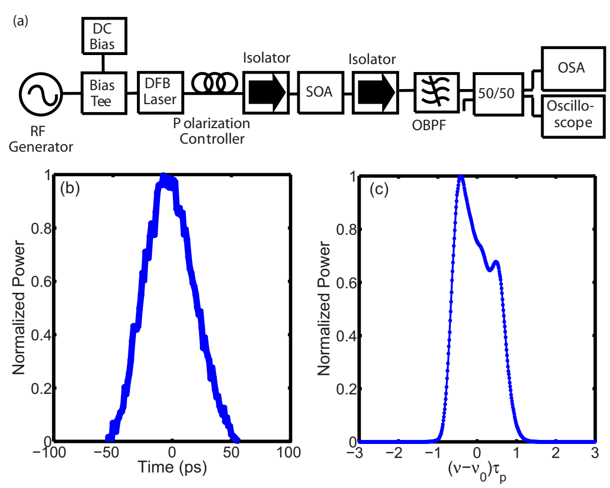

Fig. 1. (Color online) (a) Experimental setup. (b) Pulse shape and (c) pulse spectrum produced by the gain-switched DFB laser.

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poral signal was then captured by a 70 GHz sampling scope (resolution 1.25 ps). Our experiment employed a SOA with the fastest gain-recovery time of 9 ps at the maximum drive current of 500 mA. This device has been carefully optimized to produce high levels of ASE [9] and achieves its fast gain-recovery times because of gain saturation induced by a relatively large ASE power.

Figure 2 shows the remarkable evolution of the optical spectrum of amplified pulses at the SOA output as the drive current is varied from 40 to 500 mA. For the relatively low drive currents shown in Fig. 2(a), as the drive current is increased, the spectrum shifts toward the red side with more energy in the red-shifted lobe at the expense of much reduced relative energy in the blue-shifted spectral region. This kind of SPM-induced spectral change is associated with SOAs whose gain-recovery time is much longer compared to the pulse width [11]. Until recently, only these kinds of SOAs were available commercially. However, our SOA shows a dramatically different behavior for currents beyond 100 mA, as evident from Fig. 2(b). The relative energy of the redshifted spectral lobe decreases, and at the same time the relative energies in the central lobe and the blue-shifted spectral lobe increase. As a result of these changes, the output spectrum progressively becomes more symmetric at higher currents and acquires features that are typical of SPM in optical fibers [12].

Physically, changes in the pulse spectra at low and high drive currents can be explained as follows. As the leading part of the pulse saturates the gain, a red chirp is imposed on it by the carrier-induced refractive index changes governed by the linewidth enhancement factor [11]. At low drive currents, the gain-recovery time is slow, and the trailing part of the pulse therefore does not experience significant blue chirp, resulting in an asymmetric pulse spectrum. For standard SOAs, this spectral asymmetry increases with increasing drive currents [11]. For ultrafast SOAs, with increasing drive current, the ASE power increases [10], which reduces the gain-recovery time. This enhanced gain recovery imposes a blue chirp on the trailing part of the pulse and increases the spectral symmetry in the output spectrum. This situation is similar to that occurring for optical fibers in which SPM is due to the quasi-instantaneous Kerr-type nonlinearity, resulting in a much more symmetric spectrum [12].

To quantify the extent of spectral changes with increasing drive current, we plot in Fig. 3 the amplitudes of the three spectral lobes relative to the maximum spectral power corresponding to each spectral measurement as a function of the drive current. At the lowest drive current of 48 mA, the amplitudes of the blue and central lobes are smaller than the red peak but still large enough that the spectrum can be classified as a three-peak spectrum. With increasing drive currents, but below the 100 mA level so that ASE power is relatively small, relative amplitudes of the blue and central lobes decrease rapidly, and the spectrum is dominated by a single redshifted peak. At drive currents beyond 100 mA, the ASE power level begins to significantly increase the gain-recovery time of our SOA. This feature causes a remarkable change in the amplitudes of the three spectral peaks; the relative amplitudes of the central and blue spectral lobes increase rapidly. Beyond a 300 mA drive current, the amplitude of the red-shifted spectral lobe becomes lower than that of central spectral lobe, which evolves to become the highest spectral peak, resulting in a much more symmetric pulse spectrum. As is known from the case of optical fibers [12], a symmetric spectrum is the sign of a nonlinear process that responds almost instantaneously. In our case, the gain-recovery time of 9-ps at the maximum drive current becomes much shorter than the width of optical pulses (57 ps), and the spectrum, thus, begins to exhibit features that correspond to a fast nonlinear process.

We also find that reduced gain-recovery time affects the SPM-induced spectral broadening. To quantify this, we employ the first and second moments of the experimentally observed spectrum $S(\nu)$. These moments are defined as

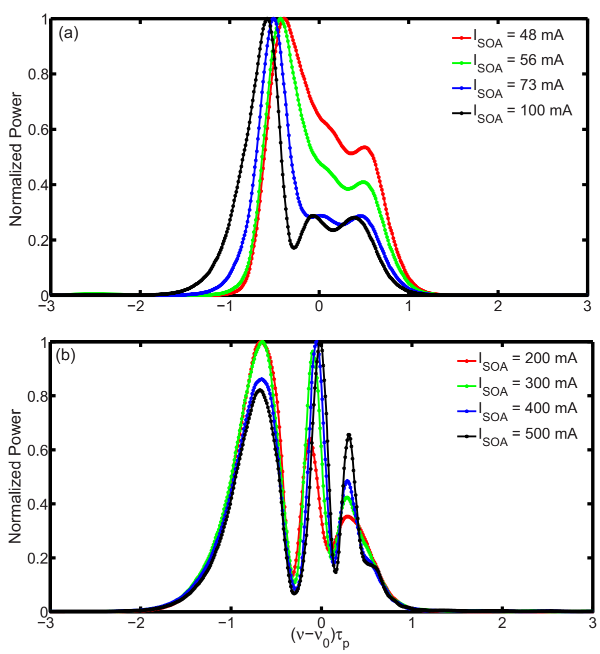

Fig. 2. (Color online) Observed spectra of amplified pulses at drive current (a) up to 100 mA and (b) beyond 100 mA.

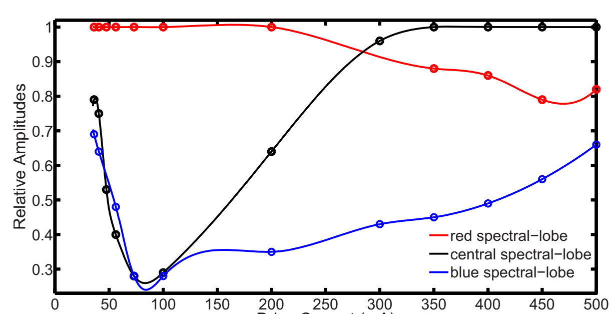

Fig. 3. (Color online) Relative amplitudes of the three main spectral lobes seen in Fig. 2 as a function of drive current.

$$\mu_n = \frac{\int_{-\infty}^{\infty}(\nu - \nu_n)^n S(\nu)\mathrm{d}\nu}{\int_{-\infty}^{\infty} S(\nu)\mathrm{d}\nu}, \tag{1}$$

where $n=1$ or 2. The two moments can be used to find the spectral width $\delta\nu=(\mu_2-\mu_1^2)^{1/2}$. We define the spectral broadening factor (SBF) as $\mathrm{SBF}=\delta\nu_{\mathrm{out}}/\delta\nu_{\mathrm{in}}$ and calculate its value as a function of the drive current.

Figure 4(a) shows the how the SBF changes with current. At low drive currents ($I<100$ mA), SBF increases almost linearly with the drive current, but it begins to saturate at higher drive currents. To understand this saturation behavior, it is important to understand the impact of ASE on the SOA's amplification factor defined as $\mathrm{G}=10\log_{10}(P_{out}/P_{in})$. The experimental setup shown in Fig. 1(a) was used to carry out this measurement with minor modifications to accommodate CW light injection. To ensure that the CW signal, launched at the SOA input at a wavelength of 1594.4, does not saturate the amplifier gain, its power, P_{in}, was limited to only 2 μW. Figure 4(b) shows the measured small-signal amplification factor as a function of drive current. This curve shows that the signal is amplified exponentially (or linearly on the decibel scale used) for currents up to 100 mA, but this exponential growth is reduced dramatically at higher currents because of gain saturation induced by the increasing ASE. The extent of SPM-induced spectral broadening achievable from any SOA depends on the SOA amplification factor, in addition to other parameters such as the linewidth enhancement factor [11]. Thus the ASE-induced gain saturation limits the SBF at the same time it improves spectral symmetry by reducing the gain-recovery time. This trade off cannot be avoided in SOAs that employ ASE for faster gain recovery.

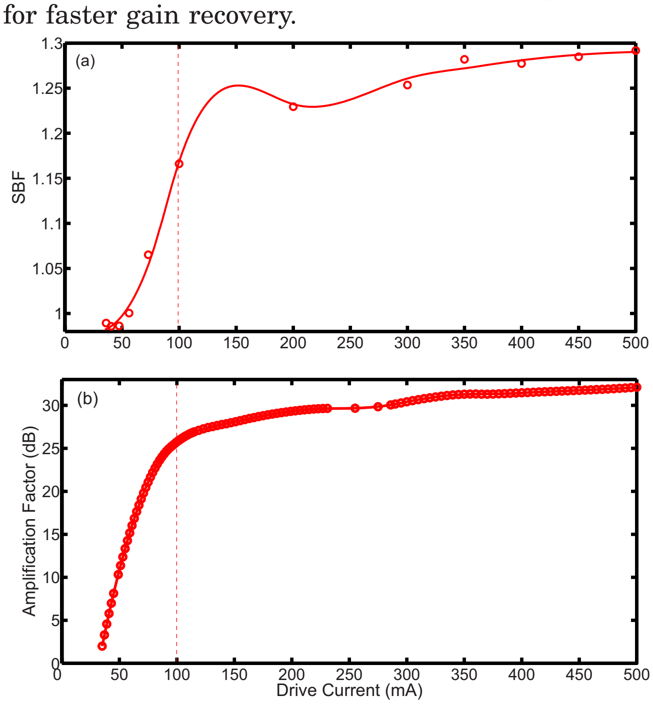

Fig. 4. (Color online) (a) Spectral broadening factor (SBF) and (b) measured small-signal amplification factor as a function of drive current.

Note the significance of the 100 mA drive current. This drive current, at which the amplification factor in Fig. 4(b) saturates, partitions the gain-recovery dynamics of our 9 ps SOA into slow and fast regimes. As seen in Figs. 3 and 4, the nonlinear response of the SOA changes remarkably at a current level around 100 mA. More specifically, the SOA behaves like a traditional slow gain-recovery SOA below this level but its gain-recovery time shortens above 100 mA, reaching a value of 9 ps at 500 mA.

To conclude, we have demonstrated experimentally that the saturation of SPM-induced spectral broadening and improvement of symmetry depends on the drive current for SOAs that employ ASE for shortening the gain-recovery time. In these devices, at high drive currents, gain recovery happens at time scales shorter than typical pulse widths employed in modern telecommunication systems. While this study has been done for a particular device length, its impact can be understood by noting that increasing device length increases the ASE power, which potentially can further reduce the recovery speed. We have shown that there is a trade off between improvement in spectral symmetry and the extent of spectral broadening. Understanding this trade-off is important for designing ultrafast, SOA-based, signal-processing techniques such as wavelength conversion and regeneration.

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