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Acceleration of Gain Recovery in Semiconductor Optical Amplifiers by Optical Injection Near Transparency Wavelength

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***Abstract*—By using optical injection near the transparency wavelength of semiconductor optical amplifiers, we show experimentally that both the saturation output power and the gain recovery can be greatly improved. By injecting 80 mW of pump power, we observe a 3-dB increase in saturation output power. For 73 mW of pump power, we find a reduction in gain recovery time from over 200 ps down to below 40 ps, while maintaining 14 dB of fiber-to-fiber gain at 1555-nm wavelength.**

***Index Terms*—Gain recovery, optical injection, saturation output power, semiconductor optical amplifier.**

I. INTRODUCTION

IT IS EXPECTED that future high-speed telecommunication systems will use all-optical technologies to avoid costly electrooptic conversions. Semiconductor optical amplifiers (SOAs) can be used to perform a variety of all-optical functions, such as wavelength conversion, regeneration, and switching. They have the advantage of being compact, consume low-power, and can be used over a wide wavelength range. For many high-speed applications, the SOA must have a fast gain recovery to avoid system penalties arising from bit pattern dependencies [1]. The gain recovery of SOAs is limited by the carrier lifetime, which itself depends on the applied current and the optical intensity in the active layer. A high current provides a large carrier density and also a high amplified spontaneous emission power, both of which tend to shorten the carrier lifetime. Therefore, to obtain a fast gain recovery, a high current must be applied. Another way to enhance the gain recovery is by increasing the optical intensity in the active layer. This leads to a higher stimulated recombination rate, and therefore, to a shorter carrier lifetime. The optical intensity can either be generated inside the SOA, or injected into the SOA from an external laser. The first case is the so-called gain-clamped SOA (GCSOA) which has distributed Bragg reflector (DBR) gratings to make the SOA lase at a wavelength offset by a few tens of nanometers from the gain peak [2]. The gain of GCSOAs is fixed by the device design and is lower than for an SOA. The GCSOAs can have high optical intensities, and therefore, fast gain recovery, but the internal lasing mode leads to relaxation oscillations in the gain recovery. The second case, where the optical intensity is injected into the SOA by an external laser, is more flexible as the gain of the SOA is not fixed by the design and the wavelength of the external laser can be changed. The gain recovery of the externally injected SOA exhibits an exponential recovery without oscillations. Several research groups have reported theoretical and experimental results on externally injected SOAs. It has been shown that the injected light accelerates the gain recovery [3]–[6], enhances the gain linearity [7], and increases the saturation output power [4], [7]–[9]. The injection wavelength is typically chosen in the gain region [9], [10], or toward the transparency wavelength , [4]–[8]. In the latter case, the required optical injection power will be high, but the available gain of the SOA will also remain high [4], [6], [8]. By using a wavelength around the gain maximum, the required acceleration can be obtained with small optical injection power, but the gain of the SOA is greatly reduced. In this article, we report experimental data for optical injection around the transparency wavelength. By using a high-power pump laser, we obtained an increase in saturation output power of 3 dB and a reduction in gain recovery time from more than 200 ps to less than 40 ps, while maintaining a fiber-to-fiber gain of 14 dB at 1555 nm. To the authors' knowledge, this is the first time that such large improvements are reported while maintaining useful gain in the 1550-nm wavelength band.

II. EXPERIMENTAL RESULTS

The experiments are performed on a 2-mm-long polarization independent bulk SOA. The maximum operation current is 450 mA, for which the device has a fiber-to-fiber gain of 21 dB at 1555 nm, and a gain maximum of 28 dB at 1510 nm. As discussed in [6], an important parameter for external pumping is the material transparency wavelength ($\lambda_{\mathrm{tr}}^{\mathrm{mat}}$), where the material gain is zero. We measured this wavelength by injecting light from a tunable laser together with a weak continuous-wave (CW) signal at 1550 nm into the SOA. When the tunable laser reaches the material transparency wavelength, the cross-gain modulation induced on the 1550-nm signal will vanish. At 150 mA of SOA current, we find $\lambda_{\mathrm{tr}}^{\mathrm{mat}} = 1486$ nm and at 450 mA $\lambda_{\mathrm{tr}}^{\mathrm{mat}} = 1454$ nm. Another parameter introduced in [6] is the device transparency wavelength where the fiber-to-fiber gain is zero. Due to coupling and waveguide loss, this wavelength is higher than the material transparency wavelength. At 150 and 450 mA, we obtained 1506 and 1463 nm, respectively. By using a commercially available 1480-nm pump laser, we are able to achieve high optical injection powers, while

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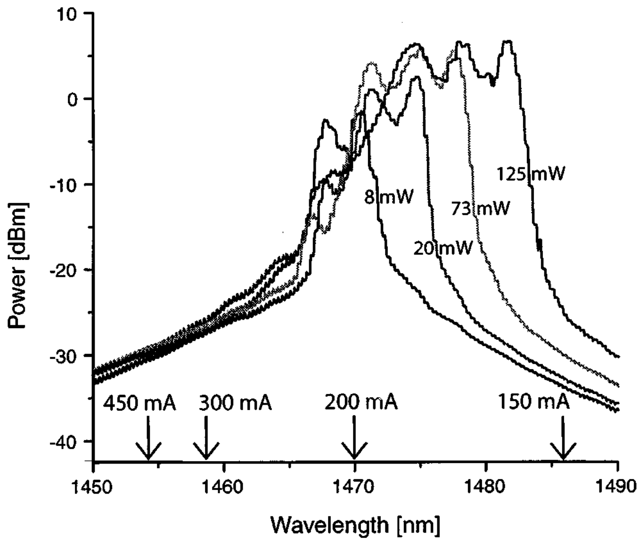

Fig. 1. Pump output power spectrum for different output powers. On the x axis the material transparency wavelengths are indicated for four different SOA bias currents.

the pump can be set in the absorption, transparency, or gain region by adjusting the bias current of the SOA. The pump output power spectrum is shown in Fig. 1 for different output powers. The wavelength of the pump is around 1470 nm at low output powers and shifts to 1480 nm at higher output powers. From this figure, it is also seen that the spectral width of the pump light increases from around 4 to 10 nm when increasing the output power. The material transparency wavelength for four different SOA bias currents is indicated in the same figure.

First, we characterize the gain saturation curve of the SOA as a function of applied current and pump power. The pump power is injected counterpropagating to the 1555-nm signal power via a 1480/1550 wavelength-division-multiplexing (WDM) coupler. The saturation curves for different pump powers are shown in Fig. 2 for SOA bias currents of 150 and 450 mA. The signal wavelength was set to 1555 nm. At 150 mA of SOA current, the pump is in the absorption region for output powers below 80 mW and approaches the material transparency wavelength at 80 mW of output power, due to its output power dependent wavelength shift (cf. Fig. 1). From Fig. 2(a), it is seen that the small signal gain varies less than 1 dB with pump power, which confirms that the pump is very close to transparency. The 3-dB saturation output power is increased from +2 to +5 dBm by injecting 80 mW of pump power. At 450 mA of SOA current, the pump is always in the gain region, and therefore, the small signal gain decreases with increasing pump power. Without the pump, the small signal gain is 21 dB and at 80 mW of pump power it is reduced to 14 dB. The 3-dB saturation output power is increased from +10 to +13 dBm by injecting 80 mW of pump power. These results confirm that optical injection can increase the saturation output power of SOAs [4], [7]–[9], and therefore, reduce interchannel crosstalk in WDM applications [10]. However, a higher saturation output power also means that more input power is needed to induce a π phase shift as needed for interferometric switching applications [3].

In a second experiment, we use a similar setup to characterize the gain recovery of the SOA as a function of applied current

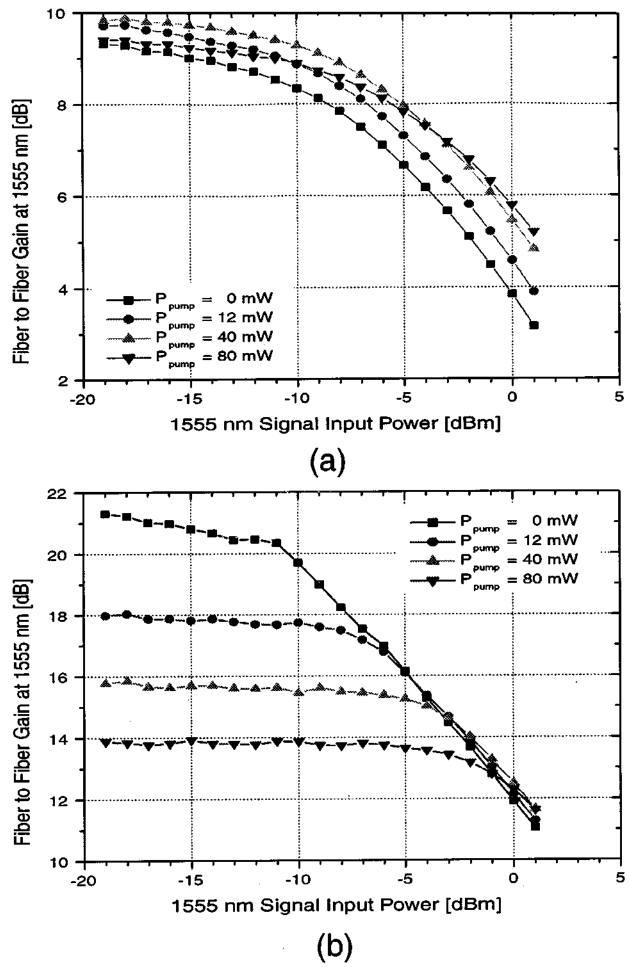

Fig. 2. Saturation behavior of the SOA for different injected 1480-nm pump powers. (a) SOA current is 150 mA. (b) SOA current is 450 mA.

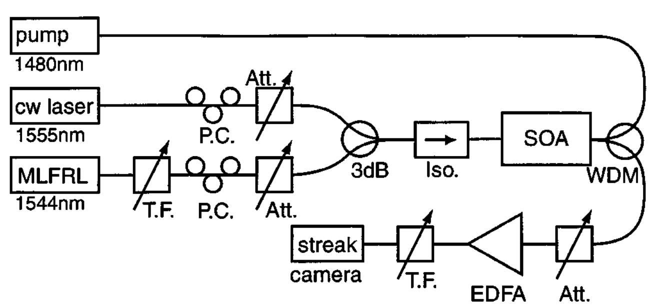

Fig. 3. Experimental setup used for the gain recovery characterization of the SOA with 1480-nm pump injection. MLFRL = mode-locked fiber ring laser. P.C .= polarization controller. T.F. = tunable filter. Att. = attenuator. Iso. = isolator. WDM = 1480/1550 coupler.

and injected pump power. The setup is shown in Fig. 3. We use an actively mode-locked fiber ring laser to generate 3-ps pulses with a repetition rate of 2.5 Gb/s at 1544 nm. These pulses induce a gain depletion in the SOA, and the recovery of this depletion is probed by a weak signal, generated by a tunable laser set at 1555 nm. The 1480-nm pump power is injected in a counterpropagating scheme via a 1480/1550 WDM coupler. A filter at the output removes the 1544-nm pulses and a streak camera detects the 1555-nm probe signal. The estimated time resolution for the experiment is 8 ps.

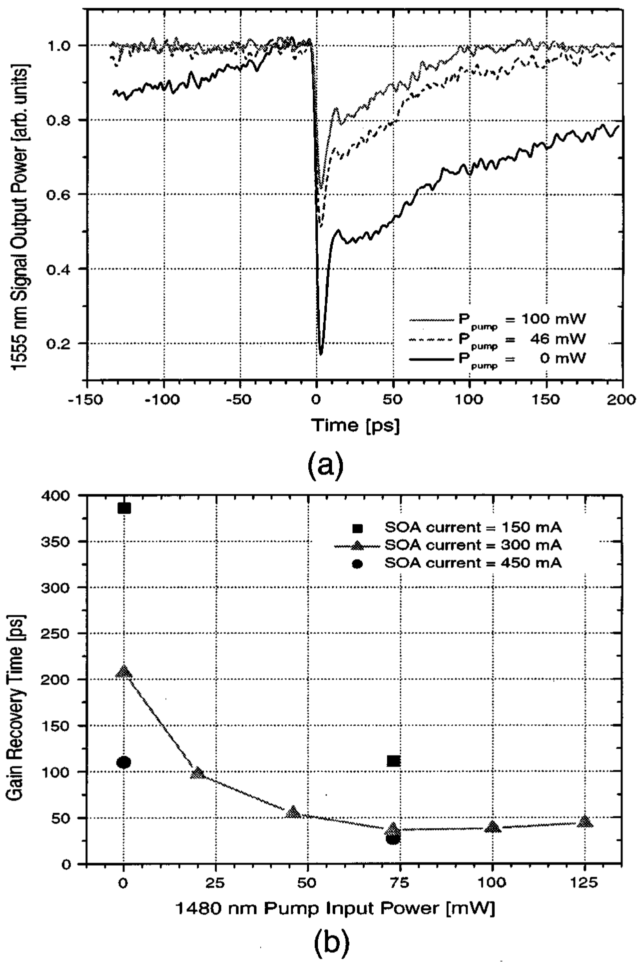

Fig. 4. (a) Streak camera measurement of the gain recovery for a SOA current of 300 mA with no pump input power and 73 mW of pump power. (b) Extracted exponential gain recovery time as a function of injected pump power for different SOA currents.

In Fig. 4(a), the gain recovery of the SOA is shown for a bias current of 300 mA. In the absence of 1480-nm pump power, the signal has not yet reached its steady-state after a full period of 400 ps, as indicated by the increase of the signal output power for negative times. The extracted gain recovery time is 207 ps without 1480 pump, and is reduced to 39 ps by injecting 100 mW of pump power. Similar results were obtained for SOA bias currents of 150 and 450 mA. The extracted gain recovery times for all currents are shown in Fig. 4(b). The gain recovery acceleration saturates for higher input powers and beyond 73 mW, no further improvement in speed is observed. By injecting pump powers of 73 mW or more, the gain recovery speed was improved by up to a factor of five, depending on current. As expected, the fastest gain recovery (27 ps) was obtained at the highest SOA current. From Figs. 2(b) and 4(b), it is seen that at 450 mA of SOA current and injection of around 75 mW of pump power the small signal fiber-to-fiber gain is 14 dB, the 3-dB saturation output power is 14 dBm, and the gain recovery time is 27 ps. This type of SOA performance is very useful for high-speed all-optical signal processing applications.

With the pump set close to transparency, one may expect that multiple SOAs can share the same optical pump. However, by measuring the pump output power, we find a very strong nonlinear attenuation of the 1480-nm pump, even at 450 mA of SOA current when the pump is in the gain region. At 450 mA, the pump output power is around 16 mW for input powers ranging from 20 to 126 mW. The origin of this strong nonlinear absorption is not clear, but may be due to two-photon absorption [11] and prevents the pump output power from being used to pump a second SOA.

In summary, we have demonstrated that optical injection of 80 mW near the transparency point of SOAs can improve the 3-dB saturation output power by 3 dB, and the gain recovery can be accelerated by a factor of five to values as low as 27 ps, while maintaining a useful gain of 14 dB in the 1550-nm wavelength band.

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