SOAs for All-Optical Switching-Techniques for Increasing the Speed

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ABSTRACT
This paper reviews some of the most recent methods for increasing the speed of operation of all-optical switches based on semiconductor optical amplifiers (SOAs). We concentrate on two approaches; namely, methods to utilise the high-frequency tail of the nonlinear optical response of SOAs, and ways to reduce their gain recovery time.
Keywords: semiconductor optical amplifier, wavelength conversion, all-optical signal processing.

1. INTRODUCTION

Semiconductor optical amplifiers (SOAs) are widely studied as nonlinear elements for high bit rate all-optical switching applications, such as wavelength conversion and regeneration [1-3]. At rates which are currently of interest (>40 Gbit/s), the natural recovery time of the gain of SOAs (typically ~100 ps) is the chief limitation to their practical implementation as switches. Many established switching schemes use interferometric structures which incorporate SOAs. These schemes exploit the significant optical phase shift in an SOA during gain recovery to rapidly alter the intensity at the output port of an interferometer, thus enabling switching. When data trains are used to switch these devices, the slow SOA lifetime leads to patterning in the gain and phase response of the SOA [2], and hence in the output from the interferometric switch. In order to prevent such patterning, a faster response speed is generally required. Recently, various linear spectral filtering schemes [1-3] have been reported which greatly increase the observed response speed. Another scheme giving a faster response incorporates a second SOA in the so-called Turbo-Switch arrangement, in which the second SOA may be loosely regarded as a filter [4, 5]. Whilst these approaches help to increase the operating speed of the optical switching, they do not reduce the actual recovery time of the gain of the SOA. To achieve this, other techniques such as a holding beam [6] and optimisation of the SOA structure [7-10] may be used.

This paper will review these different approaches. Firstly, in section 2, we consider the high-speed gain and phase response of an SOA. Section 3 will describe the filtering scheme, and in section 4 we describe the Turbo-Switch arrangement. Section 5 will discuss ways of increasing the recovery rate of an SOA.

2. SOA HIGH-SPEED RESPONSE

The response of the gain and phase of an SOA to a short (~ 1 – 2 ps) optical pulse is shown in Fig. 1. For wavelength conversion applications, the gain and phase changes are imparted onto a continuous-wave (CW) probe beam.

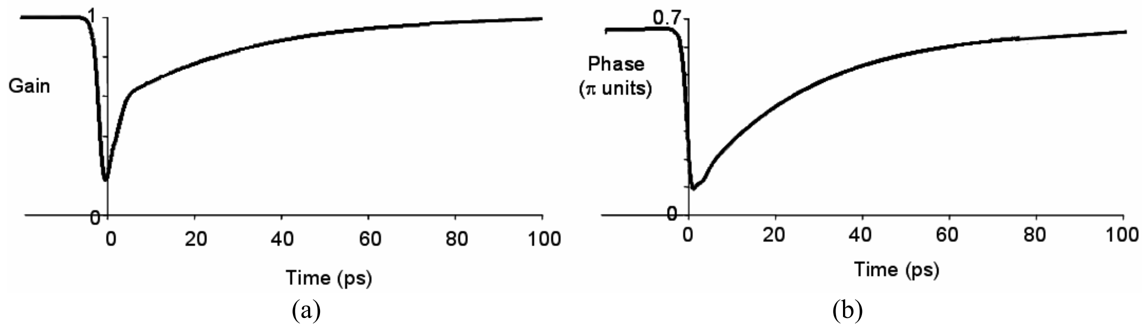

Figure1. Typical (a) gain and (b) phase response of an SOA to a ~2 ps optical pulse

The gain recovery typically has two components; one ultrafast, due to cooling of hot carriers, and the other a slower component due to electrical carrier injection. The phase has the same two components, but with a relatively much reduced ultrafast component due to the much lower refractive index change associated with carrier heating. We will refer to these two response characteristics extensively in this paper. Essentially our goal is to exploit only the ultrafast component and to minimise the influence of the slow component.

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3. FILTERING SCHEMES

The linear filtering technique described by Liu, *et al.* [1] exploits the chirp dynamics imposed upon the CW probe beam. This chirp is proportional to the time-derivative of the phase response of Fig. 1, and is shown (grey line) in Fig. 2. It has a large red (negative) component at the front of the response, followed by a rather smaller blue (positive) component. The gain response (black line) is overlaid for comparison.

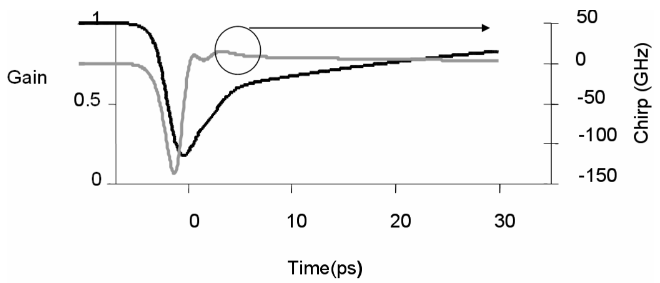

Figure 2. Gain (black line) and frequency shift (grey line) corresponding to the phase shift of Fig.1.

To exploit the chirp response, the simple filtering scheme of Fig. 3 is used. A narrow band pass filter (~1 nm) is offset to the blue side of the CW probe wavelength. An asymmetric Mach-Zehnder interferometer or delay-interferometer-signal wavelength conversion (DISC), which may also be regarded as a filter in the frequency domain [2], is placed after the band pass filter.

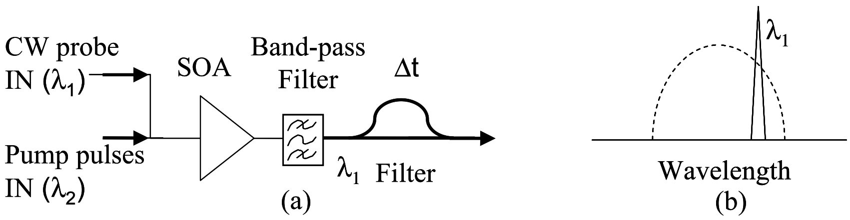

Figure 3. (a) Use of a pass-band filter and DISC filter to pass parts of the modulated CW probe spectrum [1]. (b) Placing of the CW wavelength to the blue side of the filter pass-band (dotted line).

The output from the band pass filter is a short inverted pulse. This occurs because the red chirp imparted onto the CW beam moves it outside the filter pass-band, thus lowering the output power from the filter. The subsequent rapid recovery of this red shift pushes the CW beam back into the pass band of the filter, increasing its power after the filter, which is also increased due to the ultrafast recovery of the SOA gain. A fast recovering symmetric response with a width comparable to that of the pump pulse is thus observed. The DISC inverts this negative going pulse, hence giving a short output pulse. This arrangement has been used for wavelength conversion at bit rates as high as 320 Gbit/s, albeit with a 10 dB penalty [1]. A drawback of this scheme is that the band-pass filter removes power due to suppression of part of the signal spectrum, resulting in reduced optical signal to noise ratio [2]. Other sophisticated linear filtering schemes which pass and recombine both red and blue shifted parts of the spectrum have also been reported [3], but with the drawback of a complex filter construction.

4. THE TURBO-SWITCH

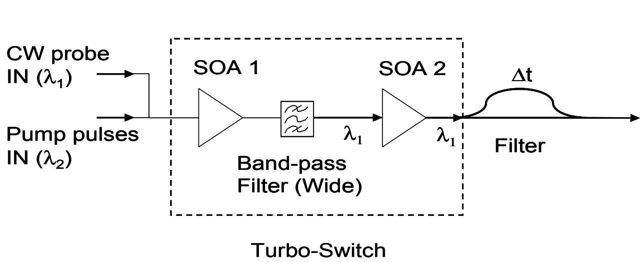

Figure 4. Turbo-Switch scheme. A DISC filter is placed after the Turbo-Switch for wavelength conversion.

An alternative approach to improve the SOA's effective response speed is to use the Turbo-Switch arrangement, shown in Fig. 4 [4]. The CW probe has gain and phase modulation imposed upon it by the response of SOA1 (see Fig. 1). The wide band-pass filter (~5 nm) used here blocks the pump, but is sufficiently wide to pass the entire modulated spectrum of the CW probe. The gain response of SOA2 is shown in Fig. 5*a*, and is now quite different to the response of SOA1. It is this gain that acts upon the modulated CW beam (a selfgain response), and the effect is to act in opposition to the slow recovery component of the amplitude and phase modulation. The effect is to considerably enhance the high-speed response of the SOA combination (Fig. 5*b*).

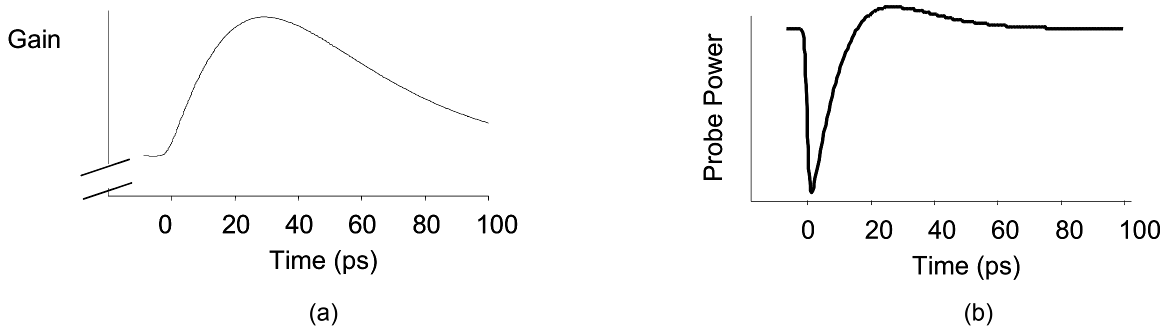

Figure 5. (a) Gain response of SOA2 to the modulated CW input from SOA1.
(b) Overall Turbo-Switch response.

The phase response is very similar to the gain response. Comparing this to the filtering technique of section 2, it may be seen once again that much of the ultrafast response of SOA1 has been preserved, whilst the effect of the slow response has been mostly suppressed. Experiments measuring the gain and phases responses of the Turbo-Switch have verified the predictions of Fig. 5*b* [5].

As already mentioned, patterning effects in SOA1 still occur. However Fig. 6*a*, which shows the power and phase of the output from the Turbo-Switch in response to an input data train, illustrates that the patterning of the power is in the opposite sense to that normally observed. Here the power minimum progressively increases with each successive pump pulse after the first. When this output is used in conjunction with a DISC, we may use the Turbo-switch for wavelength conversion. The phase differences between the two arms of the DISC interferometer lead to the formation of a patterned set of switching windows. However, the power acts now in the opposite way, tending to balance the effect of diminishing phase differences in a pulse sequence and giving a relatively unpatterned output [4].

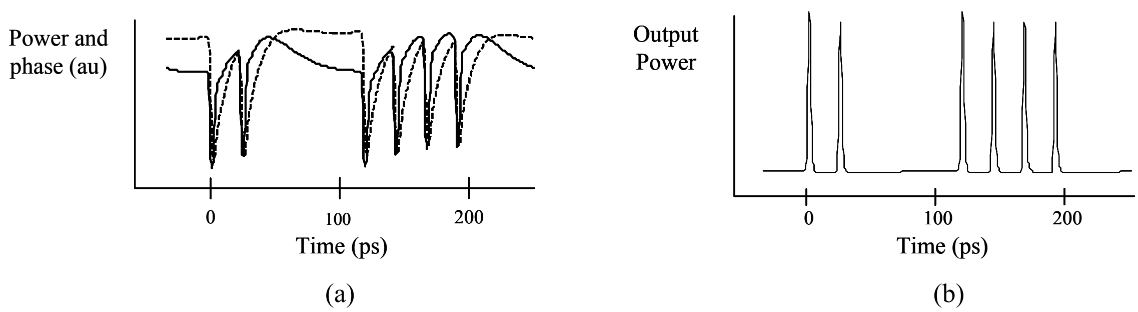

Figure 6. (a) Power output (solid line) and phase (dashed line) from the Turbo switch. The reduction in phase change for successive pulses is compensated by larger optical power (b) Power output from interferometer.

A Turbo-Switch arrangement has been used for wavelength conversion at 170 Gbit/s with 3 dB penalty [4]. The DISC was made with birefringent polarisation maintaining (PM) fibre, giving different path lengths for the two orthogonal polarisations, and a polariser, which forms the interferometer. In the case of [4], the PM fibre was placed between the two SOAs, and the polariser, which completes the interferometer, was placed after the SOA2, hence distributing the DISC throughout the Turbo-Switch. This appears to further ameliorate patterning. It should be noted that the DISC filter itself removes power from the signal, as it necessarily translates the modulated CW signal into well shaped pulses of a few ps in duration. The ultimate switching rate achievable with the Turbo-Switch is under investigation. It appears to offer a 3 – 4 times improvement in bandwidth compared to one SOA.

Returning to the filtering approach of Fig. 1, we see that patterning will also still occur in the SOA for data streams. Modelling implies that patterning is reduced in this case because the reduced probe amplitude following the second and subsequent pulses in data sequences is compensated for by larger blue shifts, due to accumulated gain saturation. There is clearly a similarity between the two schemes, both methods relying on a fortuitous balance of the gain and phase (or chirp) dynamics to give an output with low patterning.

5. SOA DESIGN

The schemes we have described so far are ways of increasing the effective response bandwidth of the SOA, without actually changing the fundamental response of the SOA itself. An alternative approach is to increase the speed and hence bandwidth of the SOA by design of the active waveguide. The effective lifetime τ_{eff} of the SOA in the presence of a CW holding beam [6] or with amplified spontaneous emission [7-9] is given by:

$$\frac{1}{\tau_{eff}} = \frac{P}{E_{SAT}} = \frac{\Gamma}{A}\frac{gP}{h\nu}, \qquad [1]$$

where P is the power of the CW beam or ASE, Γ is the confinement factor, g is the differential gain, $h\nu$ is the photon energy, and A is the cross-sectional area of the active waveguide. In order to minimise τ_{eff} we may maximise g [7], maximise Γ with a separate confinement heterostructure (SCH) layer, or, in the absence of a SCH layer, minimise the optical area (A/Γ) [8-10]. Fig. 7 shows the predicted trends from optimisation of the optical area of a bulk GaInAs device of depth 0.1 μm [10].

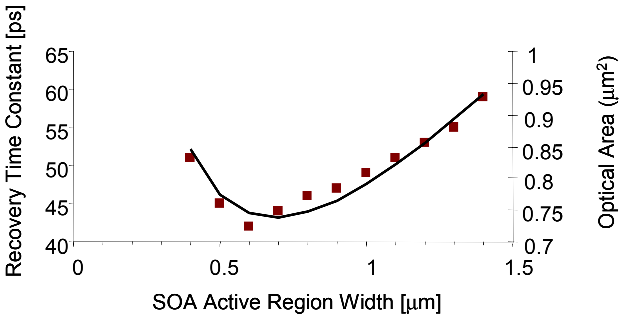

Figure 7. Modelled recovery time constant as a function of active region width (points), and modelled area to confinement factor ratio (solid line) overlaid for comparison.

If both the depth and width of the wave-guide are optimised, we find an optimal waveguide cross-section which is a square of side ~0.3 μm. A device of these dimensions is predicted to have a gain recovery time ~ 4 times lower than the minimum of Fig. 4, and would also have low polarisation dependence of the gain [10].

6. CONCLUSIONS

In this paper we have reviewed some of the techniques currently in use which allow very high bit rate optical signal processing (~160 Gbit/s) to be achieved with SOAs in simple configurations.

ACKNOWLEDGEMENT

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