All-optical wavelength conversion plays a major role in providing the wavelength flexibility in optical communication networks. All-optical wavelength converters (AOWCs) based on cross-gain modulation (XGM) and cross-phase modulation (XPM) in semiconductor optical amplifiers (SOAs) have attracted considerable research interest. In this paper, we propose a novel scheme for cascaded wavelength conversion based on cross-gain modulation and cross-phase modulation in SOAs. The wavelength conversion operation in the proposed scheme includes two stages, that is, XGM in the first stage followed by the stage of XPM, and thus is expected to have a high ER and a large input power dynamic range simultaneously.

**Keywords:** all-optical wavelength conversion, cross-gain modulation, cross-phase modulation, semiconductor optical amplifiers

1. INTRODUCTION

All-optical wavelength converters (AOWCs) are expected to become key components in future wavelength-division-multiplexing (WDM) networks [1]. The capacity of WDM-based optical communication networks is usually limited by the number of channels that can be employed, wavelength congestion at network nodes and system management requirements for network reconfiguration on link failure [2]. Wavelength converters will increase the flexibility and the capacity of WDM networks, and could be used in wavelength routers that manage wavelength paths through optical networks based on complex meshes, rather than point-to-point architectures. However, for the traditional optoelectronic conversion methods, the conversion speed is limited by the electronic bottleneck (the upper limit is 40Gb/s). And due to their bit-rate dependence, the cost dramatically increases when the system is upgraded and the costs increase as the bit rate rises.

An all-optical wavelength converter is a device that transfers information from one wavelength to another without entering the electrical domain [3]. All-optical wavelength converters rely on nonlinear material effects to perform optical signal processing. Various materials have successfully been used to perform all-optical wavelength conversion. Mainly, we distinguish between materials relying on ultra-fast parametric nonlinear processes as e.g. exploited in nonlinear fibers [4] [5], holey fibers [6] [7], or periodically poled LiNbO₃ materials [8] [9], and non-parametric nonlinear material processes as e.g. found in semiconductor materials such as lasers [10] [11], electroabsorption modulators (EAM) [12] [13], or semiconductor optical amplifiers (SOAs) [14] [15] [16] [17] [18] [19] [20]. The former processes are ultra-fast and show relaxation times below 1 ps. The latter effects show relaxation times in the order of 10 ps and longer, yet are much stronger and thus require less optical input power may be realized with shorter devices [21].

All-optical wavelength converters that utilize nonlinearities in semiconductor optical amplifiers have attracted considerable research interest due to their integration potential and their power efficiency. Various approaches based on SOAs for realizing all-optical wavelength conversion have been proposed, such as cross-gain modulation (XGM) [14] [22], cross-phase modulation (XPM) [17] [18] [24], four-wave mixing (FWM) [19] [20] and cross-polarization modulation (CPM) [25] [26]. AOWCs based on XGM have simple configurations and have a large dynamic range of the input optical signal power but a low extinction ratio (ER) (especially for up-conversions) and a high chirp. Cross-phase modulation schemes in semiconductor optical amplifiers are a promising candidate for an all-optical wavelength conversion application, because they provide an extinction ratio enhancement for both down-conversion and up-conversion, low chirping and
high conversion efficiency. However, one problem of XPM-based wavelength converter is a relative small input power dynamic range due to its periodic transfer response. There seems to be some complementarity between XGM and XPM.

In this paper, we propose a scheme based on SOAs which has the advantages of both XGM and XPM for wavelength conversion. The wavelength conversion operation includes two stages, that is, XGM in the first stage followed by the stage of XPM.

2. OPERATION PRINCIPLE

2.1 Cross-gain modulation in SOA

The operation of this type of wavelength converter is based on the gain saturation characteristics of the SOA and is schematically depicted in Fig.1. The principle can be described as follows:

An intensity modulated input signal at wavelength $\lambda_s$ modulates the gain in the SOA due to gain saturation. A continuous wave (CW) probe beam at the desired output wavelength $\lambda_p$ is modulated by the gain variation, so after the SOA it carries the same information as the intensity modulated input signal. In Fig.1, the signal beam is propagating in the same direction as the probe beam, that is co-propagating. The input signal and the CW probe beam can also be launched counter-directional into the SOA. In the counter-directional scheme the output filter, which is needed for the co-propagation scheme, can be avoided and it is possible to convert to the same wavelength.

The main advantages of this converter are the simplicity in fabrication, the polarisation insensitivity (provided that polarisation insensitive SOA is used) and the high conversion efficiency. On the other hand, there are a number of drawbacks, such as, the converted signal has significant frequency chirp and it is inverted relative to the input signal, the noise figure is high and the extinction ratio is low due to incomplete saturation. Especially for up-conversion to longer wavelength, the extinction ratio of the converted signal is practically deteriorated relative to that of the input signal [27].

2.2 Cross-phase modulation

To overcome the problems with extinction ratio degradation for the XGM scheme, the SOA converter can be used in a cross-phase modulation mode. The XPM scheme relies on the dependency of the refractive index on the carrier density in the active region of the SOA. An incoming signal which depletes the carrier density will modulate the refractive index and thereby result in phase modulation on a CW signal coupled into the converter. The phase modulated CW signal can be demultiplexed after the converter or even better the SOA can be integrated into an interferometer so that an intensity modulated signal format results at the output of the converter [3]. In the Mach-Zehnder configuration (shown in Fig.2), the input signal is injected in the upper arm, modulates the phase of the CW beam in this arm based on XPM and results in an imbalance of the interferometer.
The XPM scheme has the distinct feature that the converted signal can be either inverted or non-inverted compared to the input signal, enabling extinction ratio regeneration of the converted signal. Normally, it is advantageous for the converted signal to be non-inverted. Moreover, this results in the best signal chirp for transmission. Another advantage of the XPM converter is its very good noise characteristics. The key drawback of the converter is the narrow input power dynamic range.

3. ANALYSIS OF THE PROPOSED SCHEME

3.1 Configuration of the scheme

Fig. 3 shows the configuration of the scheme proposed by us. A signal beam at wavelength $\lambda_1$ is fed into a semiconductor optical amplifier (SOA1), and a continuous-wave probe beam which wavelength is $\lambda_2$ is fed into SOA1 from the other facet and is propagating in the opposite direction, that is, counter-propagating. The injected signal modulates the SOA1 carriers, and thus the SOA1 gain. As a result, the CW probe is modulated via cross-gain modulation, causing inverted wavelength conversion. An optical band-pass filter (OBF) is arranged at the output of SOA1, causing an increase of the frequency response of SOA1, due to the reason which will be explained in detail in the following section. The output of the OBF is fed into a delay symmetric Mach-Zehnder interferometer (MZI) with a second probe beam at wavelength $\lambda_3$, as shown in Fig.3. In MZI, by introducing the two arms with an appropriate time delay $\Delta t$, ultra-fast operation unrestricted by the slow relaxation of a carrier density change is achieved. Generally speaking, there are two stages in wavelength conversion in the scheme, that is, XGM in SOA1 in the first stage and XPM in MZI in the second stage.

Fig. 3. Schematic diagram of the proposed scheme based on cascaded wavelength conversion. SOA: Semiconductor Optical Amplifier; OBF: Optical Band-pass Filter; OC: Optical Coupler.
3.2 Frequency response enhancement of SOA1 using OBF

It is well-known that the conversion speed of wavelength conversion based on XGM and XPM is limited by the relative slow gain recovery time of SOA. In XGM, the SOA gain saturation time is determined by the pulse duration. The SOA gain approximately reaches its maximum at the time that the input pump pulse reaches its maximum intensity. However, the SOA gain recovery time is relatively too long, typically several tens to hundreds of picosecond, as in Fig.4.

In XGM, the signal beam not only modulates the gain of the SOA, but also causes a change in the refractive index both due to depletion of the carriers. This results in a chirp in the output signal. The leading edges of the (inverted) converted probe pulse are red shifted, whereas the trailing edges are blue shifted. In reference 28, the SOA chirp has been plotted as a solid line in Fig.5[28].

If an OBF which central wavelength is blue shifted with respect to the central wavelength of the probe beam is arranged at the output of SOA1, the converted signal would recover much faster. The operation of wavelength conversion in SOA1 is schematically presented in Fig.6. The fast recovery of the wavelength converter due to the OBF can be explained as follows. In timeslot A-B, the SOA1 gain saturates, and the probe beam moves to a longer wavelength (red chirp) and thus receives more attenuation by the filter. As a result, the transmittance of the probe beam through the filter is reduced. On the other hand, when the SOA1 gain recovers from point B onwards, the wavelength of the probe beam is blue shifted, leading to an increased transmittance. If the OBF is properly selected (the slope of the OBF is especially essential), the enhancement of transmittance due to the blue chirp can compensate the gain saturation. This means that the system effectively recovers much faster than the SOA1 gain [29].

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Fig. 6 Transmittance through the OBF as a function of the time. The dotted and dashed lines are the SOA1 gain and chirp, respectively.

3.3 The delay symmetric Mach-Zehnder interferometer

Fig. 7 shows a schematic view of the delay symmetric Mach-Zehnder interferometer structure adopted in our proposed scheme. The principle is similar to that of the reference 30. First of all, in each arm of the interferometer, each $\lambda_2$ input pulse signal excites the SOA, and gives rise to a transient phase shift at $t_0$ for the $\lambda_3$ CW input light, as schematically shown in Fig. 2 (a). The rise time is determined by the input pulse width, while the recovery time is determined by the relatively long carrier lifetime. Secondly, the phase shifter gives a certain phase shift for the component in the lower arm. On the other hand, a delay time $\Delta t$ is induced between the components in two arms [Fig. (b)]. These two components interfere at the output of the interferometer, the output intensity is thus written as

$$ \left| E_{out}(t) \right|^2 = \left| \frac{1}{\sqrt{2}} E \exp[i\Psi_{upper}(t)] + \frac{1}{\sqrt{2}} E \exp[i\Psi_{lower}(t)] \right|^2 $$

$$ = 2 |E|^2 \cos^2 \left( \frac{\Psi_{upper}(t) - \Psi_{lower}(t)}{2} \right) $$

(1)

Where $E$ is the same amplitude of both upper component and lower component, $\Psi_{upper}$ is the phase of the upper component, $\Psi_{lower}$ is the phase of the lower component.

If the phase shifter induces a $\pi$ phase difference between two components, that is, the phase difference in (1) is $\pi$ at $t < t_0$, the polarity of the output signal ($\lambda_3$) would be the same as the input signal of interfere ($\lambda_2$). Once the initial phase difference is thus biased to $\pi$ at $t < t_0$, the difference remains $\pi$ at $t > t_0 + \Delta t$ as well [Fig. 7 (c)]. It is because carrier-induced phase recoveries of the two components are cancelled with each other when $t > t_0 + \Delta t$. So the output of the interferometer has a finite intensity only between $t_0$ and $t_0 + \Delta t$ [Fig. 7 (d)]. As a consequence, each input pulse generates an output pulse, which pulse width is determined by the delay time, regardless of the relatively long carrier lifetime.

3.4 The integration of XGM and XPM

In the whole scheme proposed by us, the converted signal ($\lambda_2$) based on XGM in the first stage is the input signal of MZI. It has been demonstrated that the intensity of the converted signal from XGM is mainly depends on the characteristic of SOA1 and the intensity of the probe beam ($\lambda_2$) [31]. The intensity of the signal ($\lambda_3$) from a random channel in networks has little effect on the intensity of the converted signal ($\lambda_2$). It means that the input power dynamic range of the whole wavelength conversion is restricted by XPM no longer. On the other hand the converted signal ($\lambda_2$) has a good ER due to XPM, which is different from that of XGM.

4. CONCLUSIONS

We have demonstrated that it is possible to perform cascaded wavelength conversion based on XGM and XPM. The wavelength converter is expected to have advantages of both XGM and XPM, that is, a large input power dynamic range

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and a high ER. Based on the application of an OBF and delay-interferometer, the pattern effect due to the limitation of
carrier recovery time for both XGM and XPM is also mitigated, resulting in high conversion speed.

Fig. 7. Delay symmetric Mach-Zehnder interferometer mechanism. (a) XPM induced transient phase change for λ3 CW after
SOA2 (in upper arm) and SOA3 (in lower arm). (b) Time delay between phase changes for two components (the upper
beam and the lower beam). (c) The time-dependent phase components after t₀ + Δt are cancelled with each other. (d)
Output intensity.

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