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Enhanced 40 and 80 Gb/s wavelength conversion using a rectangular shaped optical filter for both red and blue spectral slicing

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Abstract: By using a tunable filter with tunability of both bandwidth and wavelength and a very sharp filter roll-off, considerable improvement of all optical Wavelength Conversion, based on Cross Gain and Phase Modulation effects in a Semiconductor Optical Amplifier and spectral slicing, is shown. At 40 Gb/s slicing of blue spectral components is shown to result in a small penalty of 0.7 dB, with a minimal eye broadening, and at 80Gb/s the low demonstrated 0.5 dB penalty is a dramatic improvement over previously reported wavelength converters using the same principal. Additionally, we give for the first time quantitative results for the case of red spectral slicing at 40Gb/s which we found to have only 0.5dB penalty and a narrower time response, as anticipated by previously published theoretical papers. Numerical simulations for the dependence of the eye opening on the filter characteristics highlight the importance of the combination of a sharp filter roll-off and a broad passband

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1. Introduction

All-optical Wavelength Converters (WCs) are likely to become essential building blocks for future dynamic high-capacity optical networks [1]. Semiconductor optical amplifiers (SOAs) have attracted considerable research interest for wavelength conversion due to their high conversion efficiency, small size and therefore practical integration potential for fully functional systems on a chip. In that respect WC based on SOAs differ dramatically from other very successful WC methods which will not be discussed here such as the use of non-linear fibers, PPLN etc. High speed error-free wavelength conversion based on Cross-Gain Modulation (XGM) and Cross-Phase Modulation (XPM) in a single SOA using a detuned filter has been demonstrated at a speed of 80Gb/s [2] with a considerable penalty (3dB) and an inverted output signal. Non-inverted WCs based on the same principle at a speed of 320 Gb/s [3] was also demonstrated albeit with an even larger penalty (~10dB) mainly caused by the excessive losses incurred by the required polarity inverter.

The possibility to generate a non-inverted WC signal using XGM and XPM by directly filtering out either blue or red components out of the inverted probe signal at the output of an SOA based WC has been previously suggested [4] and demonstrated [5,6] at speeds up to 80Gb/s with considerable penalties (5dB OSNR penalty). In this method, the filter strongly suppresses the Continuous Wave (CW) component, dominating the inverted WC signal, replacing the need for a second stage notch filter used by schemes described earlier [2]. The filter further slices the optical spectrum of the inverted signal to leave only the spectral components at either lower or higher wavelengths, termed blue and red components respectively. The relatively large penalties, reported so far, were mainly due to the non-availability of filters which have both a broad pass band and a sharp roll-off [5,6]. Thus larger than required detuning of the filter’s center frequency from the original CW probe signal was needed in order to obtain the suppression of the CW component resulting in large attenuation of the remaining spectral components and a poor Optical Signal to Noise Ratio (OSNR). Recently we have reported on the operation of an 80Gb/s WC with low penalty based on the same principle [7].

In this paper we implement the concept of filtering the blue or red components of an inverted wavelength converted signal, using an optical filter with tunable and broad bandwidth (up to 6nm) as well as very sharp roll off (>60 dB/nm) and a >50dB rejection of remaining spectral components. In this way the unwanted CW component is strongly suppressed, as well as the undesired portion of the inverted spectrum, while the rest of the filtered spectrum suffers only a minimal insertion loss (4.5dB). Using this filter we obtained, for the blue component filtering, a penalty of 0.7dB at 40Gb/s with no apparent noise floor. For the more demanding case of red component filtering, a penalty of 0.5dB was measured at 40Gb/s, and the often described and simulated faster response is observed. Additionally, the same set-up was used to demonstrate non-inverted 80Gb/s WC with only 0.5dB of penalty based on filtration of the blue part of the spectrum, albeit with a noticeable noise floor. The importance of the filter characteristics is further analyzed using numerical simulations and gives guidelines for the minimum requirements for such a filter.
2. SOA theory and numerical simulations

Two optical signals, a CW probe and a Return to Zero (RZ) modulated pump, are launched into an SOA. Through XGM and XPM the probe signal is imprinted with an inverted pattern of the pump [8], dominated by the strong CW component. By filtering out the CW component and centering the filter on either the blue or red portions of the inverted spectrum one can obtain a regenerated replica of the original signal [4].

The position of the band-pass filter relative to the CW component of the inverted WC probe will determine the polarity and shape of the final WC signal [5]. In Figure 1, we show the gain and frequency shift (chirp) that the CW probe signal experiences during the introduction of a strong picosecond pump signal, as obtained using our numerical simulation model. Obtaining a non-inverted WC output for both blue and red shifted filter positions depends on the amount of XGM and especially XPM exhibited by the SOA. For the case of placing the filter around the longer wavelength (red component), the negative frequency shift during the drop in gain will move the CW probe into the pass band of the filter, thus generating a proportional increase in power for the probe signal in agreement with the increase in pump power (non-inverting), see highlighted area II in Fig. 1. Since the duration of red shift is very short, as it only follows the changes in gain during the existence of the pump pulse, the obtained filtered pulse will be very narrow in time. Since at the same time, gain is suppressed by the strong pump signal, the resulting non-inverted signal is considerably weak.

For the case of a blue shifted filter, the non-inverting output signal is mostly dependent on XPM. Initially the probe signal will experience a brief blue shift due to carriers generated by the leading edge of the pump pulse, see area I in Fig. 1. After this short blue shift, the pump pulse will induce a negative frequency chirp (red shift), due to strong carrier depletion which will cause the probe signal to be filtered out even more. However, during the gain recovery process, (area III in Fig. 1) the probe signal is blue chirped. During this time, the probe signal wavelength is shifted into the band-pass region and a non-inverted output pulse is obtained. However unlike the case of red component filtering, where gain is suppressed and chirp is short in time, for the blue component filtering, the opposite is true so that a much stronger pulse is available with improved OSNR but a broader response.

Fig. 1. Gain and frequency shift, experienced by the probe signal
The final shape of the time domain pulse is dominated by the duration of the blue/red chirp induced frequency change and the total bandwidth of the filter. In order to preserve the original pulse shape one needs the filter’s optical bandwidth to be in the order of the spectral width of the original RZ pulses (~5 nm). Another crucial aspect for this kind of WC scheme is the eventual OSNR obtainable as it will determine the penalty incurred. For that purposes it is desired to filter out the CW component without affecting the 1st blue/red modulation side-band as it contains most of the converted pulse energy. In order to fulfill both of the above requirements a special flat top, broad filter with sharp roll off is required [5].

In order to gain a better understanding of the requirements from this sort of filtering technique and its applicability for fast WC we used an SOA band model valid for time responses in the pico-second and sub-picosecond regime [8-11]. The SOA model includes XGM and XPM effects required to model the wavelength conversion process as well as Two-Photon Absorption (TPA) and Free-Carrier Absorption (FCA) responsible for the Carrier-Heating (CH) and Spectral-Hole Burning (SHB) effects. The equations used for generating the simulation results are detailed in [10-11].

Using the referenced model, the following WC experiment was numerically simulated. Parameters considered here for the SOA can be found in [10-13]. A 40 GHz pump signal using 2 ps Full-Width Half Maximum (FWHM) Gaussian pulses and modulated with a random bit sequence at 40 Gb/s was coupled with a continuous-wave (CW) probe at the input of the SOA. The mean optical powers were 3 dBm for the modulated pump and 2 dBm for the CW probe. Pump and probe were detuned 10 nm apart. After the propagation through the SOA a filtering stage was introduced. The filter profile was determined by the width of the pass band, the width of the transition bands, and the attenuation of the rejected band thus becoming a trapezoidal profile (see Fig. 2). The rejection of the adjacent channels was kept fixed at 50 dB. The width of the transmission and transition bands (roll-off) as well as the central frequency of the filter were varied in the simulations to evaluate the wavelength conversion process performance. Two performance figures were evaluated; the Eye Opening (EO) and the pulse width at FWHM. The EO is defined as the ratio between the minimum power of the signal pulses sequence when logical ‘1’ bits are modulated and the maximum power signal pulses sequence when logical ‘0’ bits are modulated, at the decision instant within the bit interval. In this case, the decision instant is the one that maximizes the EO. As non-inverted WC is obtained, the EO is expected to be always larger than 0 dB. The pulse width at FWHM is defined as the mean value of the time width at the half of its maximum power of the signal pulses sequence when logical ‘1’ bits are modulated.

![Fig. 2. Simulation results showing the dependence of pulse width on the filter Bandwidth](image-url)
For the case of tuning the filter bandwidth while keeping the slope constant the important performance characteristic is the pulse width (Fig. 2). The width of the output non-inverted pulse after filtration is simulated for different filter bandwidths for both blue and red components in the case of 40Gb/s RZ pump signal. Since patterning effects play a very minor role in the pulse width numerical assessment, the same pulse width is expected also for faster pulse repetition speeds. This is because for the simulation parameters used, the XPM recovery time, as seen from Fig. 1, is relatively small when compared to the bit period at 40 Gb/s repetition rate (25 psec). The filter transition band was fixed at 100 GHz forcing a numerical filter slope of 62.5 dB/nm (or 50 dB in 100 GHz). The width of the band pass was varied while holding the filter’s edge close to the CW spectral component of the probe at a constant position (see inset in Fig. 2). In the case of holding the CW component to the upper edge of the filter the blue chirp was employed to perform the non-inverted wavelength conversion. In the case of holding it to the lower edge, the red chirp was used. For the case of blue chirp filtering, the slow response time sets a lower limit (8 ps) on the pulse width which is already apparent for 200 GHz filter bandwidth. However for the case of red chirp filtering the converted signal’s pulse width is considerably narrower (<5 ps) and the filter bandwidth at which this value is achieved is almost double (around 400 GHz). Still it is obvious that the fundamental limit for the pulse width lies in the carrier dynamics of the SOA rather than the filter bandwidth.

Figure 3 shows how changing the filter’s roll-off affects both EO and pulse width. Here, the width of the band pass was kept fixed at 500 GHz and the width of the transition band was varied. Changing the roll-off we observe that EO goes from a practically closed eye for a roll off lower than 25 dB/nm to a maximum value of 10-11 dB for a slope value between 50-60 dB/nm. Increasing the roll-off further does not improve EO as it implies sharper spectral slicing which results in ripples in the time domain eye. As for the pulse width, the same values obtained in Fig. 1 are repeated with a minimum required roll-off larger than 30 dB/nm. The apparent increase/decrease in pulse width for slopes lower than 25dB/nm is meaningless since
for these values the eye is practically closes (or inverted), and only positive EO were computed as explained above.

3. Experimental set-up and result discussion

The experimental set-up is shown in Fig. 4

![Experimental set-up diagram](image)

Fig. 4. Experimental set-up (for 40Gb/s experiments the 40:80 Mux and EAM Gating are not used)

3.1 40Gb/s wavelength conversion

The 40GHz Fiber Mode Locked Laser (FMLL) RZ pulse source, with 2 ps FWHM, is externally modulated by a Mach Zehnder Modulator (MZM) by a $2^{31}-1$ Pseudo Random Bit Sequence (PRBS) at 40 Gb/s. The pump signal is coupled with the probe signal and launched into the SOA. An SOA similar to the one used in [2] was also used for this experiment. The SOA has a measured total recovery time of 56 ps when biased at 400 mA, dominated by a slow blue component. At the output of the SOA the signal is filtered by the special flat top broad band filter with roll-off > 60db/nm and a rejection greater than 50dB of adjacent channels. The signal is then amplified using and Erbium doped fiber amplifiers (EDFA) and filtered again using a standard Gaussian shaped 5 nm filter to remove excess ASE noise. Table 1 summarizes the key parameters for operating the WC for either the blue or red filtered components.

|                      | Red Component Filtering | Blue Component Filtering |
|----------------------|-------------------------|--------------------------|
| Pump Wavelength [nm] | 1560                    | 1560                     |
| Pump Power [dBm]     | 1.5                     | -6.3                     |
| Probe Wavelength [nm]| 1548.1                  | 1548.1                   |
| Probe Power [dBm]    | 1.5                     | -2.7                     |
| SOA current [mA]     | 400                     | 262.8                    |
| Filter Center Frequency [nm] | 1550.968 | 1545.858 |
| Filter Bandwidth [nm] | 4.5                     | 4.31                     |

In Fig. 5 the spectra’s for the wavelength converted signal for both filtering cases as well as the unfiltered spectrum are plotted together. The filtered spectra was taken in both cases after the EDFA so that spectral features on the edges of the filter’s band-pass are lost in the
ASE noise. Also, the power of the sidebands as it appears in the filtered spectra includes ~20dB of EDFA gain. The non filtered spectra, taken for the case of higher bias current and stronger pump power (black solid line), has a secondary peak around 1545 nm arising from non linear distortions (Self Phase Modulation) incurred by the original pump signal that are copied to the WC probe through XGM and XPM processes. In the case of filtering out the red components, these distortions are filtered out, however for the case of blue component filtering the operating conditions had to be greatly altered (8 dB drop in pump power, and 30% drop in DC bias current for the SOA), as any distortions will be included in the broad filtered output signal.

![Filtered and non-filtered spectra's at the SOA output](image)

As explained in Sec. 2, the polarity of the inverted WC signal at the output of the SOA can be flipped by removing the CW component from the signal. By using a broad filter, with very sharp roll-off, carrier rejection of more than 30dB as well as 1st and 2nd sidebands insertion losses of 10 and 5 dB respectively were obtained (the filters’ insertion loss was measured to be 4.5 dB).

![BER (left) and eye patterns for B2B (top) and Red and Blue filtered (middle and bottom respectively) Wavelength converted signals](image)
The resulting eye patterns and Bit Error Rate (BER) vs. received power given in Fig. 6, indicate that these specific filter characteristics, especially the sharp roll-off and large bandwidth, greatly improve the performance of the scheme, compared the previous works \[4-6\]. For red filtered WC there is a negligible negative penalty for BER worse than 10^{-7} but it is apparent that there is an error floor which brings the penalty for a BER of 10^{-9} to 0.5 dB. The error floor arising from the noise of the SOA is more dominant for the case of the red filtered WC since there is a power difference of 8 dB between the blue and red 1^{st} order side bands while the noise floor is the same. For the blue filtered results, a penalty of 0.7 dB is obtained and no error floor was observed. The eye patterns in Fig. 6 give an indication on the respective time domain performance for red and blue filtering. The filtering of the red components results in a much faster response with a FWHM of around 3 ps (only 1 ps more than for the original pulses, Fig. 6 top right). However for the case of filtering out the blue chirp components, which are strongly dependent on the slow recovery time of the SOA, the observed eye is much wider having a FWHM of around 4.5 ps and a pulse base duration of 12 ps.

### 3.2 80Gb/s wavelength conversion

The pump signal entering the SOA is centered around 1560 nm and has a power of 0.7 dBm. The CW probe signal was at 1548.1 nm with a power of 6.7 dBm. The same SOA was used also for this experiment. At the output of the SOA a sharp flat top 6.15 nm wide Band Pass Filter (BPF) was placed, centered on 1544.63 nm. The filter has a roll-off greater than 60 dB/nm and an insertion loss of 4.5 dB. After filtering, the 80 Gb/s signal is time demultiplexed to the 40 Gb/s original PRBS bit rate using Electro Absorption Modulator (EAM) gating, converted back to the electrical domain and tested for errors.

In Fig. 7, the inverted (before filter) and non-inverted spectra (taken directly after the BPF) are both shown. Notice the strong attenuation incurred by the CW signal (>35 dB) compared to the 9 dB (extra 4.5 dB due to detuning) attenuation of the 1st side band and no extra attenuation on higher order modulation side-bands. Also visible is the SOA noise floor at around -45 dBm, around the higher order side-bands. This noise together with the minimal impact on the 1st order side-band (-18 dBm) give an OSNR >25 dB, sufficiently good for the low penalty measured.

![Fig. 7. Spectra of the converted signal at the output of the SOA before and after the filter](image)

In Fig. 8 the BER for the two 40 Gb/s tributaries are shown (red lines) compared to their back to back counterparts (blue line). Also shown for comparison are the pump and probe eye patterns. The measured penalty is 0.5 dB and the eye is broadened from a 2 ps FWHM to
about 4.5 ps, similar to what was measured for the experiment carried out at 40Gb/s. However the converted signal suffers from poorer OSNR leading to an observable change in BER slope.

4. Conclusions

The use of smart optical filtering in order to improve and simplify all optical WCs is attractive since such filters can be designed also into integrated devices as Arrayed Waveguide Gratings. Thus a chip size wavelength converter with low penalty, as little as 0.5 dB, can be realized at speeds of 80 Gb/s. As shown in this paper, it is possible to reduce penalty to as little as 0.5 dB in the case where the optical filter has a broad bandwidth as well as a steep enough roll-off to both block the CW components and inflict a minimal insertion loss upon the 1st modulation side-band (which are only 0.6 nm apart). The importance of these two design parameters was further investigated using numerical simulation in which filter bandwidth and roll off were swept for the case of 40Gb/s non-inverted all-optical WC. The resulting minimum requirements from the simulation of >400GHz bandwidth and >40dB/nm roll-off, were in good agreement with the filter used in the experimental demonstration. Ultimately, the speed is limited by carrier dynamics and the noise generated in the SOA. For the current device poor OSNR is obtained for higher bit rates (160 Gb/s and beyond) due to the strong dependence of modulation sideband power on the modulation speed. It is thus possible that improved performance and even faster operation can be accomplished with the aid of higher output power bulk SOAs, which will improve signal power at the SOAs output or alternatively Quantum Dot amplifiers which will reduce the noise floor.
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