# All-optical Vestigial-Sideband Signal Generation and Pattern Effect Mitigation with an SOA Based Red-Shift Optical Filter Wavelength Converter

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**Abstract** *We demonstrate 40 Gb/s SOA-based wavelength conversion from a RZ into a vestigial-sideband RZ signal. SOA related pattern effects are successfully suppressed by proper choice of the red-shift optical filter.*

## Introduction

Vestigial-sideband (VSB) signals are of interest for two main advantages in optical communication systems. Firstly, they have a good spectral efficiency allowing for very dense wavelength-division-multiplexed (DWDM) transmission systems with improved tolerance to dispersion [1]. Secondly, VSB signals have favourable transmission characteristics since their phase-amplitude characteristic provides minimum inter-symbol interference (ISI) [2]. In view of the advantages of VSB signals, it would be desirable to have all-optical wavelength converters (AOWCs), which may process or generate VSB encoded signals at network nodes. Yet, if to be practical, wavelength converters need to be able to operate at 40 Gb/s and higher without the usual SOA carrier recovery related pattern effects.

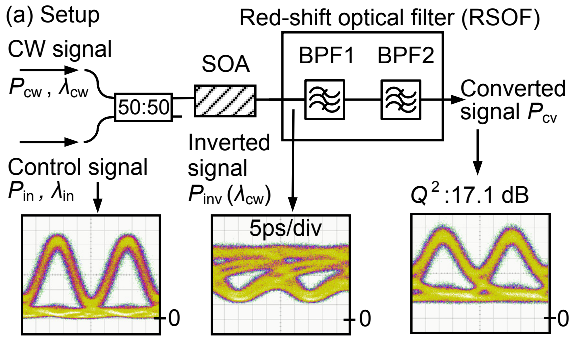
In the past, pattern effects have successfully been suppressed by taking advantage of differential schemes, see e.g. [3]. Yet, only recently it has been recognized that spectral shaping may be used for pattern effect mitigation as well [4-7]. Now, since an optical VSB signal is usually generated by using a spectrally-shifted optical filter, it seems natural to simultaneously generate a VSB signal and suppress pattern dependence in an SOA-based AOWC.

In this work, we will demonstrate VSB return-to-zero (RZ) signal generation and all-optical wavelength conversion with an SOA-based AOWCs relying on a red-shift optical filter (RSOF) scheme. Proper selection of the filter passband and slope allows for VSB generation from any on-off keying signal with simultaneous pattern effect mitigation.

## Scheme and Operation Principle of VSB Generation and Pattern Effect Mitigation Technique

The scheme for the VSB-generating AOWC with simultaneous pattern removal is shown in Fig. 1. The setup comprises an SOA followed by a RSOF. The proper shape of the RSOF has been engineered with two band-pass filters (BPFs).

(a) Setup



(b) Measured signal spectra and filter transmissions

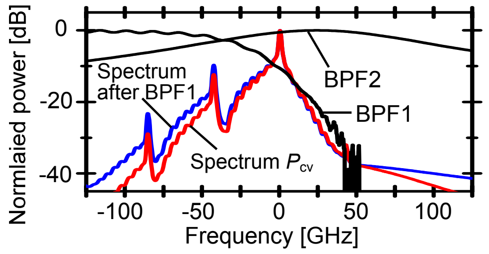


**Fig. 1** *(a) Wavelength conversion setup. BPF: bandpass filter. After the filters, an inverted signal with strong pattern effect is reshaped to non-inverted and pattern effect mitigated signal with a* $Q^2$*-factor of 17.1 dB. (b) Measured signal spectra and the respective filter transmissions.*

The VSB-generating AOWC with simultaneous pattern removal works as follows. A data signal modulates both the gain and the refractive index of the SOA thereby impressing the information in an inverted manner onto another continuous wave (cw) signal, see eye diagram $P_{inv}$ in Fig. 1(a). The leading edges of the converted light pulses are spectrally red-shifted (RS). In our scheme, we use BPF1 to select the RS spectral components and to cut off the blue-shifted spectral component in order to produce the VSB signal; see spectrum after BPF1 in Fig. 1(b).

To mitigate the SOA related pattern effects we have added a second filter (BPF2). It is noticed that the two BPFs can be replaced by a single BPF with a proper filter shape. In this work, we used two discrete BPFs. This allows us to demonstrate that the two respective slopes of the RSOF have different functions.

We now explain how the pattern effect from the SOA is mitigated by properly tuning BPF2 within the RSOF, as illustrated in Fig. 2. This is done by using the SOA model from [8]. For a given input pulse train, Fig. 2(a), the first “1” bit in the pulse train usually induces the strongest carrier depletion and the largest gain reduction Fig. 2(b). However, a strong carrier-depletion induces a large phase-shift and consequently a large red chirp on the leading edge, Fig.

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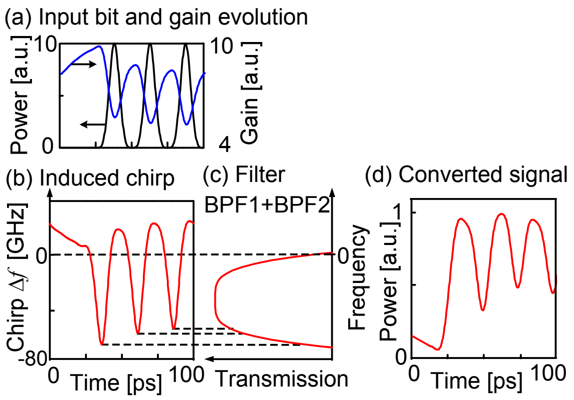

**Fig. 2** *Schematic showing the pattern effect mitigation by frequency-amplitude conversion at filter slope. (a) Input data pulse train and simulated gain evolution. (b) Induced frequency chirp in the inverted signal. (c) Schematic filter shape of the red-shifted filter. (d) Simulated eye diagram of converted signal.*

2(b). For subsequent pulses, the SOA does not fully recover, so that the gain decreases for subsequent “1” bits. As the gain decreases, the induced red chirp decreases, Fig. 2(b). The technique to overcome the pattern dependence now relies on choosing the proper slope of BPF2. Actually, it can be chosen to allow for higher transmission of weakly chirped signals and suppressed transmission of strongly chirped signals. As a consequence the power transmitted through the filter, Fig. 2(c), does not show any pattern dependence, Fig. 2(d).

### Experimental Results

For experimental verification a 33% RZ signal at a bit rate of 40 Gb/s with an average power $P_{\text{in}}$ of 12.7 dBm and a carrier wavelength $\lambda_{\text{in}}$ = 1530 nm has been launched into the SOA. The pseudo-random data with a sequence length of $2^{31}-1$ has a quality factor $Q^2$ = 19.8 dB. A cw signal with a power $P_{\text{cw}}$ of 14.7 dBm and $\lambda_{\text{cw}}$ = 1536.3 nm is coupled into the SOA. It becomes the wavelength converted signal. The signal quality of the converted signal is up to 17.1 dB. The bulk SOA of length L = 2.6 mm was biased at I = 750 mA. The non-saturated and saturated gain was 23 and 3 dB.

To verify the pattern effect mitigation technique, we detune the centre cw signal wavelength $\lambda_{\text{cw}}$, while keeping the filters and other parameters unchanged. The recorded $Q^2$-factor and bit patterns at three different positions are shown in Fig. 3. It can be seen, that the first pulse of the sequence initially is overshooting, then is equalized and ends up being suppressed when tuning the centre wavelength from $\lambda_{\text{cw}}$ = 1536.0 nm to 1536.4 nm. There is an operation wavelength range of ~0.2 nm within which the $Q^2$-factor is above 15.6 dB.

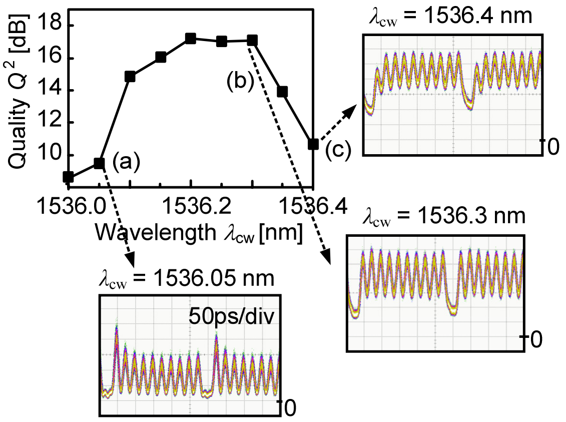

**Fig. 3** *Signal qualities of the red-shifted signal for various cw wavelengths without adaptation of filter parameters. The pattern effect is successfully mitigated at (b) $\lambda_{cw}$ = 1536.3 nm, but not compensated at (a) $\lambda_{cw}$ = 1536.05 nm, or over-compensated at (c) $\lambda_{cw}$ = 1536.4 nm.*

To verify whether the output signal really is a VSB signal, characterization of the spectrum shown in Fig. 1(b) is not enough. As shown in [2], a VSB RZ signal is essentially a RZ signal with $\pi/2$ progressive phase shift (PPS). This $\pi/2$ PPS as a matter of fact provides the reduced ISI due to destructive interferences from neighbouring pulses. Therefore we determined the amplitude and phase characteristic of the converted signal for two repetitive patterns “1111” and “1010” [9]. The measurements depicted in Fig. 4(a) and (b) clearly show a $-\pi/2$ and a $-\pi$ phase shift between the respective marks, which actually translates into a $-\pi/2$ PPS from bit to bit. This corresponds to the ideal PPS for a VSB as shown in [2].

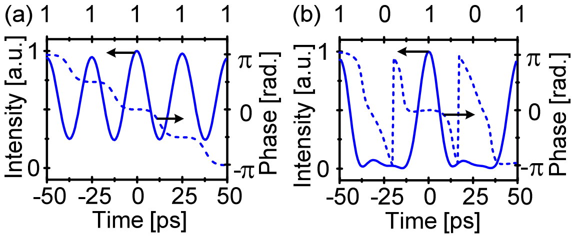

**Fig. 4** *Measured $\pi/2$ progressive phase shift of the VSB signal with a bit pattern: (a)1111 and (b) 1010.*

### Conclusion

An SOA-based AOWC generating a 40Gb/s VSB RZ signal was demonstrated. Bit pattern effects were also successfully mitigated by carefully arranging a red-shift optical filter.

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