Field Trial Experiment over 1200 km on a 100GHz Grid-Aligned Multi-Channel Black-Box Wavelength Converter

Victor J. F. Rancaño*, Francesca Parmigiani, Periklis Petropoulos, David J. Richardson
Optoelectronics Research Centre, University of Southampton, UK
**vjfr1u10@orc.soton.ac.uk*

Abstract: A flexible modulation-, bit rate- independent and polarization insensitive wavelength converter based on a highly nonlinear fiber is demonstrated in the middle-point of a field trial transmission experiment.
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1. Introduction

Wavelength conversion is a functionality of primary importance in optical networking, especially after the introduction of automatically switched optical network (ASON) meshes. However, for any optical wavelength conversion solution to be considered practical it must be easily reconfigurable, insensitive to the polarization of the signals and operate with minimal degradation of system performance [1].

Polarization insensitive wavelength conversion schemes based on four-wave mixing (FWM) have recently been reported [2,3], however they have typically required tight filtering at the idler wavelengths to adequately eliminate the pump radiation, compromising their suitability for any real system use. This limitation can be overcome by placing the pumps of the FWM system further apart and this has been demonstrated, albeit to date for CW signals only [4]. Of course, in this case it is far more challenging to achieve phase matching in the FWM process.

In this paper we demonstrate a black-box, multichannel, modulation format and bit-rate independent wavelength converter (WC) that can be used directly with wavelength division multiplexed (WDM) signals aligned to a 100GHz ITU grid, and measure its performance in a 1200-km transmission experiment over installed fiber. The WC is based on the use of FWM in a highly nonlinear fiber (HNLF) pumped by two orthogonally polarized, widely frequency-spaced pump beams placed outside the signal wavelengths. The large spacing between the two pumps in conjunction with the use of two different arrayed waveguide gratings (AWGs) allows simplified filtering of the signals and multichannel operation. This configuration also provides sufficient flexibility for the WC to be incorporated in an optical add-drop multiplexer (OADM), or in a reconfigurable OADM (ROADM).

For our transmission experiments the black-box WC was placed at the mid-point of an installed fiber link. The WC performance in transmission was identical to that achieved in purely lab-based experiments, providing a flat conversion gain of -2 dB across the whole conversion band of 10nm and a polarization dependent loss (PDL) of 0.64 dB.

2. Experimental Set-up

The schematic of the WC is shown in Fig 1. It comprised two AWGs which were configured to couple the signals together with two orthogonally polarized pump beams (linewidth of 100kHz) into a HNLF and an output filter to allow all the filtered idlers through simultaneously. The two pumps were set at 1562.23 nm (191.90 THz) and

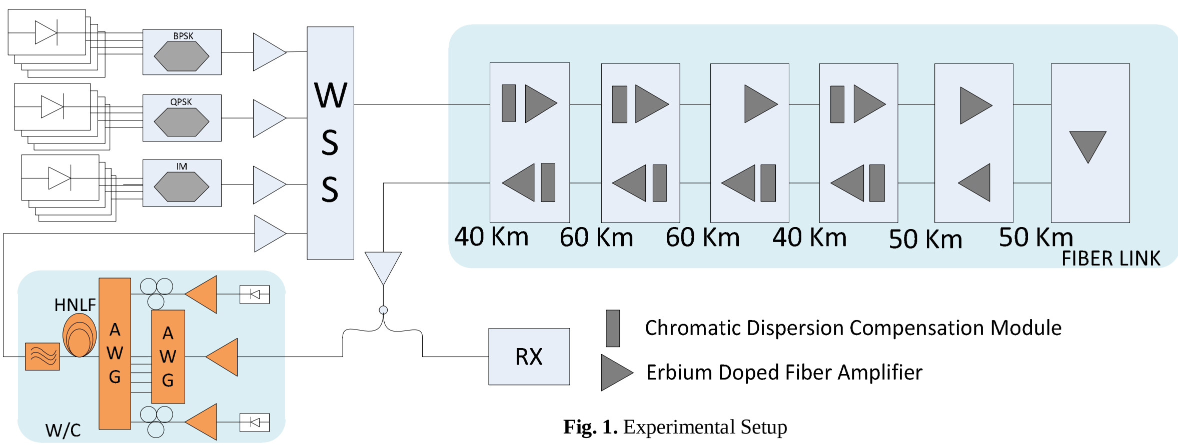

Fig. 1. Experimental Setup

1550.12 nm (193.30 THz), and the input channels were between 1559.79 nm (192.2 THz) and 1556.55 nm (192.60 THz) so that the wavelength converted signals lay between 1555.75 nm (192.70 THz) and 1552.52 nm (193.10 THz).

The input signals were amplified together up to a level of 5dBm per signal and filtered by the AWGs to remove the amplified spontaneous emission (ASE). The initial removal of ASE within the bandwidth of the wavelength converted signals is critical since without this the conversion power penalty increases by 5-6 dB. Note that just a single amplifier could be used for all the input signals due to the channelized filtering characteristics of the AWG. The second AWG also facilitated filtering of the ASE of the pumps, which were amplified up to a power of 21.5 dBm each at the HNLF input. The (flat-top) coarse output filter was tuned to cover the entire output bandwidth.

The 302m-long HNLF used was a germanium-silicate dispersion-shifted, strained fiber with a stimulated Brillouin scattering (SBS) threshold of 27 dBm. The nonlinear coefficient of the fiber was 11.6 $(W\cdot km)^{-1}$, the dispersion slope 0.018 ps/($nm^2\cdot km$) and the zero-dispersion wavelength after the straining was 1555 nm.

The WC was used as a black-box device at the middle of an installed link (the UK Aurora dark fiber network) to assess its performance (see Fig.1). Six data signals were used in our transmission experiments, three of which were wavelength converted after transmission over 600km, coupled with the original six channels and re-transmitted over the same distance. The fiber link comprised twelve spans, as shown in Fig 1, with distances ranging between 40 and 60 km each. The data signals were modulated using three different modulators to generate on-off keyed (OOK), binary phase shift keyed (BPSK) and quadrature phase shift keyed (QPSK) signals. The signals were amplified and filtered using a wavelength selective switch (WSS) with a filter resolution of 50 GHz. The launched power per channel was 2 dBm. After traversing the loop a second time, the converted signals were received, characterized in terms of constellation diagrams and bit-error rate (BER) and their performance was compared to that of the signals both after a first circulation around the loop and after passage through the WC. The chromatic dispersion in the link was not fully compensated to reduce nonlinear effects so that a receiver with chromatic dispersion estimation and compensation was used to properly receive the signal after the first loop and after the wavelength converter.

Note, however, that digital dispersion compensation was not required for the WC signals after the second passage through the loop since the WC conjugated the phase of the original signal at the mid-point of the system after the first circulation [5].

3. Experimental Results

In order to test the performance and robustness of the setup two different kinds of tests were performed. First, the WC was tested under single channel operation. Subsequently, the system was characterized for two distinct network scenarios involving the simultaneous conversion of three channels, which were dynamically reconfigured thanks to the flexibility provided by the WSS. Different modulation format signals at different wavelengths and bit rates were considered in each case.

Single Channel Performance

Under single-channel operation, the WC was tested using various modulation formats (OOK, BPSK, QSPK and 16-QAM) and different symbol (Gbd) and net data rates (Gbit/s). We found that signals operating up to 40 Gbit/s QPSK could be clearly detected after wavelength conversion and re-transmission. Wavelength conversion of 10Gbd 16-

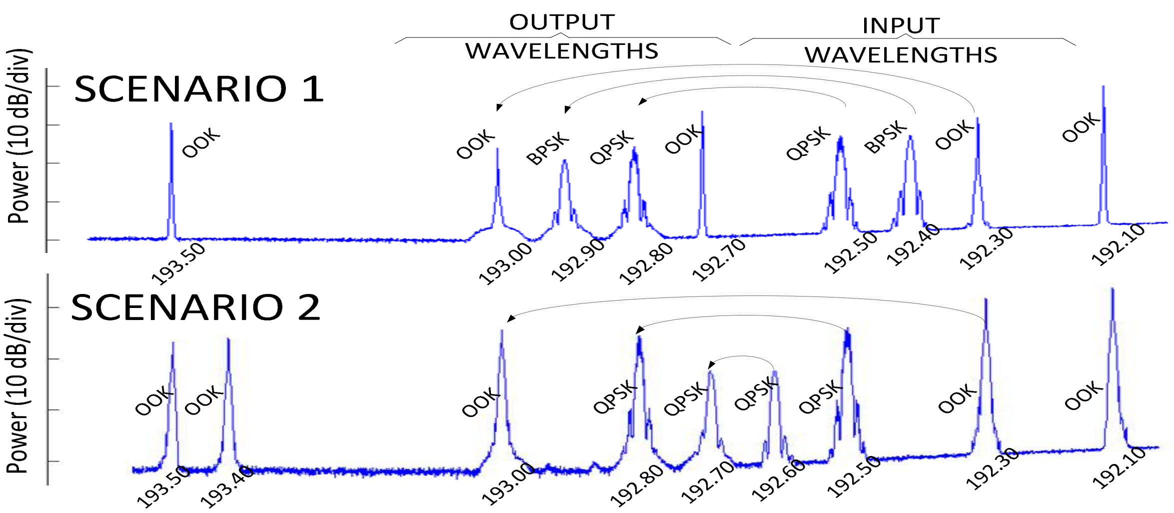

Fig. 2. Spectral traces and diagrams after the link transmission for the two proposed scenarios.

QAM signals was also achieved but, due to its higher signal-to-noise ratio requirements, it could not be used in our field trial experiments. Changes in the state of polarization of the incoming signal caused a variation in the conversion gain of just 0.64 dB. The WC was tested under two different scenarios of multi-wavelength operation (Fig.2).

Scenario 1

The first scenario highlights the modulation-independence and the multichannel operation of the scheme. In this scenario four non-return-to-zero (NRZ)-OOK signals at frequencies 192.1, 192.3, 192.7 and 193.5 THz, one NRZ-BPSK signal at frequency 192.4 THz and one NRZ-QPSK signal at frequency 192.5 THz were transmitted through the link. The rate of all signals was 10 Gbd. The signals at 192.3, 192.4 and 192.5 THz were chosen to be converted to 193.0, 192.9 and 192.8 THz respectively. One of the non-converted OOK signals was intentionally allocated in the output bandwidth of the WC to prove that any possible interference from the WC did not affect the transmission performance.

The bit error rate (BER) measurements of the BPSK and QPSK signals for the back-to-back (B2B), after the first transmission (600km), the wavelength conversion (600+WC) and the second loop transmission (1200km) are shown on the left of Fig. 3. The BERs of the OOK signals could not be assessed at the intermediate stage because of the residual chromatic dispersion. After the second loop their BER was below the FEC threshold of 10^{-3}.

Scenario 2

The second scenario highlights both the wavelength selectivity and multichannel conversion of the scheme. In this scenario the same four NRZ-OOK signals and two NRZ-QPSK signals at frequencies 192.5 and 192.6 THz were transmitted through the link. The rate of all signals was again 10 Gbd. The signals at 192.3, 192.5 and 192.6 THz were chosen to be converted to 193.0, 192.8 and 192.7 THz respectively.

The BER measurements of the QPSK signals for the back-to-back (B2B), after the first transmission (600km), the wavelength conversion (600+WC) and the second loop transmission (1200km) are shown on the right of Fig 3. As discussed previously the OOK signals were not characterized at the intermediate stage, however their performance after the second passage through the loop was similar to that in scenario 1.

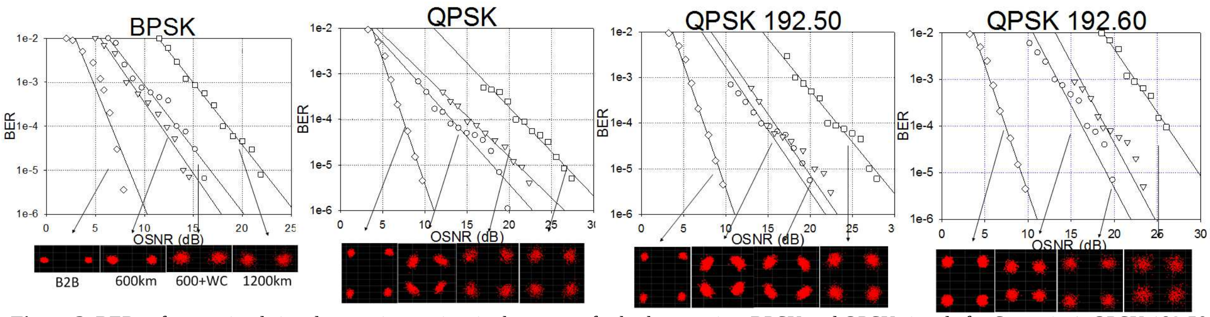

Figure 3. BERs of transmitted signals at various points in the system for both scenarios: BPSK and QPSK signals for Scenario 1. QPSK 192.50 and QPSK 192.60 signals for Scenario 2

4. Conclusions

A new wavelength conversion scheme capable of multichannel operation and independent of the configuration at the input has been presented and experimentally tested in the mid-point of an installed transmission link. The performance of the WC is identical to that achieved in laboratory experiments, exhibiting flat conversion gains of -2dB across the whole conversion band of 10nm (limited only by the choice of pump wavelengths) and PDL values of 0.5 dB. These experiments demonstrate that all-optical wavelength conversion solutions have reached a sufficient level of technological maturity to be considered for deployment in real systems.

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