All-optical wavelength conversion for mode division multiplexed superchannels

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Abstract: We report in this work the first all-optical wavelength conversion (AOWC) of a mode division multiplexed (MDM) superchannel consisting of $2N$ modes by dividing the superchannel into $N$ single-mode (SM) tributaries, wavelength converting $N$ SM signals using well developed SM-AOWC techniques, and finally combining the $N$ SM tributaries back to an MDM superchannel at the converted wavelength, inspired by the idea of using SM filtering techniques to filter multimode signals in astronomy. The conversions between multimode and SM are realized by 3D laser-writing photonic lanterns and SM-AOWCs are realized based on polarization insensitive four wave mixing (FWM) configuration in $N$ semiconductor optical amplifiers (SOAs). As a proof of concept demonstration, the conversion of a 6-mode MDM superchannel with each mode modulated with orthogonal frequency division multiplexed (OFDM) quadrature phase-shift keying (QPSK)/16 quadrature amplitude modulation (QAM) signals is demonstrated in this work, indicating that the scheme is transparent to data format, polarization and compatible with multi-carrier signals. Data integrity of the converted superchannel has been verified by using coherent detection and digital signal processing (DSP). Bit error rates (BERs) below the forward error correction (FEC) hard limit ($3.8 \times 10^{-3}$) have been obtained for QPSK modulation at a net bitrate of 104.2 Gbit/s and BERs below the soft decision FEC threshold ($1.98 \times 10^{-2}$) have been achieved for 16-QAM format, giving a total aggregate bit rate of 185.8 Gbit/s when taking 20% coding overhead into account. Add and drop functionalities that usually come along with wavelength conversion in flexible network nodes have also been demonstrated. The working conditions of the SOAs, especially the pump and signal power levels, are critical for the quality of the converted signal and have been thoroughly discussed. The impact of imbalanced FWM conversion efficiency among different SM tributaries has also been analyzed. This work illustrates a promising way to perform all-optical signal processing for MDM superchannels.

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1. Introduction

Wavelength conversion (WC) has long been recognized as a desirable functionality to increase the flexibility of dynamic wavelength-routed networks [1]. Recently, space division multiplexing (SDM) [2] using multi-core fibers [3] or multi-mode multiplexing (MDM) [4] or a combination of both [5–7] has been widely explored as a promising solution to go beyond current single mode fiber capacity that is known to be limited by fiber nonlinearities. MDM technologies, in particular, rely on the use of the spatial modes of multimode waveguides as an additional degree of freedom to increase the transmission capacity on top of well-developed multiplexing techniques such as wavelength division multiplexing (WDM). However, spatially multiplexed channels are susceptible to modal crosstalk. The fact that mode coupling is inevitable along transmission implies that the different wavelength channels can be routed to different destinations but that all the spatial modes present on each wavelength should remain together to facilitate multiple-input multiple-output (MIMO) processing at the receiver [2]. Such a wavelength channel containing few-mode tributaries is called a MDM superchannel [8]. Add and drop functionalities are key to today’s flexible photonic mesh networks based on reconfigurable add–drop multiplexers (ROADMs). Several demonstrations of upgrade of the functionalities of single-mode ROADMs to the case of MDM systems using MDM superchannels as basic processing units have already been reported [8–10]. It is therefore natural that, in order to further increase the flexibility of mode- and wavelength-multiplexed networks, WC should also be performed on the basis of MDM superchannels. However, such a functionality has, so far, never been demonstrated.

The methods for realizing WC can be classified into two categories, i.e. optical-electrical-optical (O-E-O) WC and all-optical WC (AOWC). O-E-O WC means that optical signals have to be converted to electrical signals and processed in the electrical domain before being converted back to the optical domain. Comparing to the slow response time of optoelectronic/electronic devices, AOWC is especially attractive due to its capability to perform WC of a signal with large bandwidth since ultrafast nonlinear effects such as the Kerr effect can easily accommodate signal symbol rates beyond the Tb/s level [11, 12]. In addition, the configuration of WC in the MDM scenario may differ from that of the single mode (SM) case. As shown by Fig. 1(a), O-E-O WC requires 2N pairs of transmitters and receivers, where N is the spatial modes supported by multimode fibers with two fold polarization degeneracy in each mode. That is, the number of required optoelectronic devices
scales with $2N$ in the O-E-O solution. An ideal AO solution would utilize, on the contrary, a single piece of multimode nonlinear element (MM-NE) to perform WC for all modes simultaneously. Numerical investigation of such multimode wavelength conversion has been reported recently for the case of $N = 3$ by W. Pan et al. [13]. Furthermore, one benefit in favor of O-E-O is that it enables data regeneration, especially the retiming and reshaping functions (often called “2R” and “3R”). However, bit level information has to be retrieved in order to harvest these benefits. Digital signal processing (DSP) with $2^N \times 2^N$ MIMO algorithm is thus necessary in this sense to unmap the scrambled modal information due to unavoidable random mode mixing occurring along the fiber link, as shown by the dashed box in Fig. 1(a). Therefore, the benefit of data regeneration guaranteed by O-E-O operation would be significantly more complex to achieve in the MDM-OEO scenario than in the SM-OEO case.

Format transparency is an important feature that a properly designed AOWC unit should possess. This is because optical communication systems have migrated from binary modulation formats such as the on-off keying (OOK) or the differential phase-shift keying (DPSK) format to complex modulation formats where information is coded both on the amplitude and phase of the electrical fields. Multi-carrier signals, in particular orthogonal frequency division multiplexing (OFDM), have also been widely investigated due to their distinctive advantages such as high spectral efficiency, resilience to dispersion effects, etc [14]. In addition, polarization-division multiplexing (PDM) has been widely adopted, indicating that the MDM-AOWC unit should be polarization insensitive (PI). Coherent WC enabled by four-wave mixing (FWM) in $\chi^{(3)}$ media, or equivalently by cascaded second order nonlinear processes in $\chi^{(2)}$ media, has shown to be a good candidate to fulfill all the above requirements when PI schemes are used [15–17]. However, to implement the MDM-AOWC scheme illustrated in Fig. 1(a), achieving efficient FWM for all the spatial modes in a single MM-NE appears to be quite challenging. This is because good phase matching should be achieved for all modes in order to ensure efficient FWM processes, which would require proper design of the dispersion of the nonlinear waveguide [13,18,19]. It might be extremely challenging to achieve good phase matching for all modes when $N$ becomes large. To overcome this issue it may be intuitive to first demultiplex an MDM superchannel into SM tributaries so that AOWC can be performed for each tributary individually using SM-AOWC techniques before they are multiplexed back to the MDM superchannel again, as shown in Fig. 1(b). Note that such benefit are achieved at the price of utilizing more SM-NEs. However, it may scale with $N$ rather than $2^N$ as required by its O-E-O alternative if PI schemes are adopted.

In this work, we show experimentally that the data integrity of the MDM superchannel is preserved after performing coherent AOWC in $N$ single mode nonlinear elements (SM-NEs). The information of the MDM superchannel is successfully recovered at the converted wavelength based on coherent detection and MIMO processing. To show that the proposed scheme is transparent to modulation format, polarization, as well as compatible with multi-carrier signals, we choose the PDM-OFDM signals loaded with quadrature phase-shift keying (QPSK) or 16 quadrature amplitude modulation (QAM) formats in this work. Actually there is no need to perform strict mode multiplexing and demultiplexing since modes are mixed already before entering the first MMUX in the WC. As shown in Fig. 1(c), adiabatic tapers (ADTs) are used instead of MMUXs in this demonstration by making use of photonic lanterns (PLs). Unlike traditional MMUXs that suffer from mode combining losses that scales exponentially with $N$, PLs do not directly address/extract individual modes and theoretically allow lossless transition from multimode to single mode given that $N \leq M$, where $M$ is the number of single mode fibers at the output of the PLs [20, 21]. Therefore, on top of the benefit of low loss, the SM-AOWCs of the scheme is mode transparent in the sense that exact modal information is not relevant to the FWM processes in the SM-NEs ($N$ needs to be known ahead though in order to decide the required number of SM-NEs). The idea is very similar to the invention of PLs for applications in astronomy where both multi-mode fibers
(MMFs) and SM fibers (SMFs) are highly desirable and a way of light conversion between MMFs and SMFs is hence required [20, 21]. Furthermore, add and drop functionalities required by an MDM-ROADM can be easily integrated into the proposed MDM-AOWC scheme. They have also been demonstrated in this work.

![Fig. 1](image.png)

**Fig. 1.** (a) Comparison of wavelength conversion (WC) of an MDM superchannel by O-E-O conversion and all-optical (AO) WC using a single multimode nonlinear element (MM-NE). (b) and (c) are MDM-AOWC schemes using single mode (SM) NEs. MM to SM conversion is achieved by mode multiplexers (MMUXs) in (b) and adiabatic tapers (ADTs) in (c). (d) Cross polarized dual pump FWM scheme for SM-AOWC used in this work. MMUXs are used to accomplish conversion between multimode and single mode signals. MMF: multimode fiber; Rx: receive; Tx: transmit; DSP: digital signal processing; MIMO: Multiple-input multiple-output. PBS: polarization (pol.) beam splitter. SOA: semiconductor optical amplifier.

### 2. Transfer matrix of MDM-AOWC

A linear MIMO system can be described by its transfer matrix (TR). Since FWM is known to be a good candidate for format transparent WC, we focus on the TR of an MDM-AOWC enabled by the FWM effect shown in Fig. 1(c) in each SM tributaries. In order to be compatible with PDM signals, PI-FWM is ensured in this work by using two pumps with orthogonal polarization states (labelled here as X and Y polarizations), as shown in Fig. 1(d) [15]. The electrical field ($E$) of the idler can then be expressed as

$$
E_{\text{idler},y} \propto E_{p1,y} E_{p2,y} E_{\text{sig},x}^* \\
E_{\text{idler},x} \propto E_{p1,x} E_{p2,x} E_{\text{sig},y}^*.
$$

Therefore, the TR of AOWC in the $i$th SM tributaries, denoted by $T_i$, becomes

$$
\begin{bmatrix}
E_{\text{idler},x} \\
E_{\text{idler},y}
\end{bmatrix}
= 
\begin{bmatrix}
0 & \eta_{yx} K \\
\eta_{xy} K & 0
\end{bmatrix}
\begin{bmatrix}
E_{\text{sig},x} \\
E_{\text{sig},y}
\end{bmatrix}
= T_i
\begin{bmatrix}
E_{\text{sig},x} \\
E_{\text{sig},y}
\end{bmatrix},
$$

where $\eta_{yx}$ ($\eta_{xy}$) represents the FWM efficiency of generating the converted signal in the $y$($x$) polarization when the input signal is in the $x$($y$) polarization. $K$ denotes the complex conjugate operator. Therefore, the total TR of $N$ SM-WC, $T_{SMWC}$, can be written as

$$
T_{SMWC} = 
\begin{bmatrix}
T_1 & 0 & \cdots & 0 \\
0 & T_2 & 0 & \vdots \\
\vdots & 0 & \ddots & 0 \\
0 & \cdots & 0 & T_N
\end{bmatrix}.
$$

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The time delay as well as the phase shift among $N$ SM tributaries induced by different path lengths and environment variations are ignored in Eq. (2) and Eq. (3). A properly designed PL features low transmission loss as well as low mode-dependent loss (MDL) [22], an effect that would increase system outage probabilities and deteriorates the system capacity [23, 24]. In case no MDL and transmission loss are present in the PL, the TR of a PL can be expressed as an unitary matrix, denoted by $U$ in the following discussions. The TR of a PL is defined as the TR from the multimode input of the PL to the single mode outputs of the PL. Therefore, the total TR of the MDM-AOWC, $T_{\text{MDMWC}}$, becomes

$$T_{\text{MDMWC}} = U T_{\text{SMWC}} U \quad (4)$$

If the conversion efficiencies of both $x$ and $y$ polarization of all $N$ wavelength converters are all equal to $\eta$, $T_{\text{MDMWC}}$ becomes the product of a scalar $\eta$ with $U$ and the capacity of links employing such a WC can be maximized. This has been verified by intentionally setting unequal working conditions to three SM-NEs, as will be discussed in section 5.

### 3. Characterization of the SM-AOWCs

A variety of nonlinear platforms have been investigated for SM-AOWC exploiting FWM or cascaded second order nonlinear processes for single-carrier or multi-carrier signals using amplitude and/or phase modulation, such as highly nonlinear fibers (HNLFs) [25, 26], bismuth oxide-based nonlinear optical fibers [27], periodically-poled lithium niobate (PPLN) waveguides [28], chalcogenide fibers [29], silicon waveguides [30, 31], III-V nanowires [32], semiconductor optical amplifiers (SOAs) [33, 34] etc. Integration is a key driving force for keeping reducing the cost and energy per bit when upgrading current systems to SDM systems. FWM in SOAs offers a simple coherent operation in a compact device that could be potentially integrated with other photonic devices and could achieve efficient WC at remarkably low pump power levels compared to passive platforms [35]. Therefore, SOAs have been chosen as the main nonlinear elements in this work.

The experimental configuration used for SM PI-FWM is shown in Fig. 1(d). Since $N$ is chosen to be three in this demonstration, the same number of SOAs are needed in this work. Our implementation relies entirely on commercially available SOAs: two SOAs are from CIP (SOA-NL-OEC-1550, labeled A and B) and the third one is from Kamelian (SOA-NL-L-C-FA, labeled C). All SOAs are operated with a bias current of 210 mA unless otherwise specified. Such current level has been found to be sufficient to provide reasonable FWM efficiency. The specified polarization dependent saturated gains (PDGs) of the CIP and Kamelian SOAs are smaller than 1 and 2 dB, respectively. The total power levels at the SOAs inputs are limited to 10 dBm to avoid device damage. Since phase noise transfer from the pumps to the converted signal is critical to complex modulated signals, the linewidth of the two pump lasers that are used for each SOA is 100 kHz, which is much smaller than the requirement given in [36]. FWM processes are evaluated by conversion efficiencies (CEs), defined as the ratio between the power of the idler at the output of the SOA to the signal power at the input of the SOA. Figure 2 shows the CEs of the three SOAs under various wavelength allocations. The maximum CE difference among three SOAs fluctuates around 6 dB in most cases. To satisfy $\eta_1 = \eta_2 = \cdots = \eta_N$ as discussed in section 2, erbium-doped fiber amplifiers (EDFAs) are used after SOAs for all channels to compensate the inherent CE differences of the SOAs, as will be discussed in sections 4 and 5. The polarization dependences of the CE are measured to be 3 dB for SOA-A and 4 dB for SOA-B and SOA-C. The maximum CEs with respect to polarization dependences are always represented in Fig. 2 for consistency.

Figure 2(a) shows the CE as a function of the frequency detuning ($\Delta f$) between pump 2 and signal while keeping the frequency spacing between pump 1 and pump 2 fixed at 125 GHz (1 nm). The pump and signal power at the input of each SOA are set to 5 dBm and 1.8
dBm, respectively. The FWM CE drops quickly as the signal moves away from pump 2 at a similar rate for all SOAs. By using SOAs with better design or other platforms such as highly nonlinear fibers with zero and flat dispersion, it is possible to greatly enhance the acceptable bandwidth of the signal, i.e. the separation between pump 2 and the signal. On the other hand, the detuning between idler and signal can be increased significantly by fixing the frequency detuning between pump 2 and signal at 87.5 GHz (0.7 nm) while increasing Δf between the two pumps, as shown in Fig. 2(b). The pump power at the input of each SOA is set to be the same as in Fig. 2(a) while the signal power at the input of each SOA is −3 dBm in this case, resulting in a few dB difference in the CEs shown in Fig. 2(a) and 2(b) for identical wavelength allocations. Such CE difference resulting from different signal power levels is in agreement with the pump and signal power dependence measurements of the CE illustrated in Fig. 3. Nevertheless, the 3 dB CE bandwidths of the three SOAs are all found to be larger than 1 THz (~8 nm) in this case, given a relatively large frequency detuning range between signal and converted idler with the dual pump scheme.

Figure 3 shows the saturation effects of the three SOAs at different signal power levels. For a given signal power, the CE increases as the pump power increases until a maximum CE value is reached and decreases afterwards. The pump power corresponding to the maximum CE increases as the signal power increases. However, the maximum CE decreases as the signal power increases due to gain saturation. Furthermore the CEs measured for different signal powers evolve towards a similar CE value when the pump power increases. Bit error rates (BERs) measurements given in section 5 indicate that the best performance is not obtained using pump and signal power combinations resulting in the largest CE, but at a condition corresponding to a good trade-off between cross-gain/phase modulation and CE, similarly to the phenomena observed in [33]. This will be further discussed in section 5.
Fig. 3. CE as a function of total pump power at the input of (a) SOA-A (b) SOA-B (c) SOA-C for signal power at the input of the SOAs at $-6 \text{ dBm}$ (squares), $-3 \text{ dBm}$ (up triangles), $0 \text{ dBm}$ (down triangles) and $3 \text{ dBm}$ (filled circles).

4. Experimental setup

The experimental setup is presented in Fig. 4. The transmitted signal is generated off-line using MATLAB from a of $2^{31}-1$ pseudo-random binary sequence (PRBS). The data sequence is mapped to QPSK or 16-QAM constellations. The computer-generated discrete Fourier transform (DFT) OFDM QPSK/16-QAM baseband signal with 456 payload subcarriers out of 512 total subcarriers is loaded onto an arbitrary waveform generator (AWG) with sampling rate of 12 GS/s. The middle 6 subcarriers are unfilled. Meanwhile, 4 other subcarriers are used to estimate the phase noise. 1/8 of the symbol period (64 samples) is used as cyclic prefix to avoid inter-symbol interference due to channel dispersion and mode group delay. The analog RF signals produced by the AWG are then used to drive an IQ modulator. The continuous wave (CW) fed into the IQ modulator is generated by a tunable external cavity laser (ECL) emitting at 1559.1 nm with a linewidth of 100 kHz. A PDM signal is emulated by splitting the OFDM signal from the IQ modulator into two branches with 1 OFDM symbol (48 ns) delay between the two. The two tributaries are then recombined by a polarization beam splitter (PBS). An MDM superchannel is then synthesized by splitting the PDM-OFDM signal into three copies with relative delays of 96 ns (2 symbols) and 192 ns (4 symbols), respectively, before the copies are input to the SM ports of the first PL (PL1). Therefore, the raw data rate is $12 \times 2(\text{QPSK}) \times 6(\text{modes}) \times (456-6-4)/(512 + 64) = 111.5 \text{ Gbit/s}$ for the QPSK modulation MDM superchannel, and for the 16-QAM modulation MDM superchannel, the raw data rate is $12 \times 4(16\text{-QAM}) \times 6(\text{modes}) \times (456-6-4)/(512 + 64) = 223 \text{ Gbit/s}$. For the purpose of implementing the AOWC technique proposed in Fig. 1(c), the second PL (PL2) is used to divide the MDM superchannel into three SM tributaries, i.e., TA, TB and TC. The third PL (PL3) is used to combine TA, TB, and TC into an FMF after AOWC in three SOAs. As a proof of concept demonstration, PL1 and PL2 are connected directly by splicing their few mode fibers ports together. PL3 and PL4 are connected similarly. All the PLs used in this work are commercial devices from Optoscribe. The output few mode fibers of the PLs are graded-index MMFs from OFS with mode groups LP$_{01}$ and LP$_{11}$ supported. The average insertion loss is 1.1 dB across all waveguides (excluding connecting fibers) and the MDL is approximately 1.5–2 dB for each PL. Half of the signals in TA, TB and TC are tapered out by 3 dB couplers for the evaluation of the drop functionality. The other half of the signals are fed into three SOAs as probe light together with orthogonally polarized dual pump light to generate FWM idlers at the converted wavelength. Two pump signals at 1557.4 nm and 1558.4 nm are generated by two separate ECLs with linewidth of 100 kHz, combined with a PBS and then amplified by an optical amplifier (not shown in Fig. 4) before being input to the SOAs.
The SM-NE used in each SM tributary is an SOA, as discussed in section 3. After the FWM processes in SM-NEs, the converted signals are amplified by EDFA1-3 with constant gain of 17 dB to avoid optical signal-to-noise (OSNR) degradation and subsequently launched into wavelength selective switches (WSSs) to select the converted wavelength. Each WSS has four input ports and two of them are used. Three WSSs are configured identically. The first input port of each WSS was configured to pass the idler light. Therefore, signals at the converted wavelength are transmitted without loss (ideally) while the original signal as well as the pump lights are blocked. Since the original signal has been wavelength converted to a new wavelength (idler wavelength), the second input port of each WSS is utilized to enable another signal working at the same wavelength as the original signal to be added to the original data stream. For the “drop” functionality, part of the original signal is tapped at the output of PL2 so that the drop signal is not affected by the optical signal processing unit. To emulate the “add” functionality, the dropped signals are bridged directly to the second input ports of the WSSs, as shown by the dashed lines in Fig. 4. The converted signals with added signals at the output of WSSs are then amplified by EDFA4-6. Since the signal power levels measured at the output of PL2 are almost the same for the three tributaries, the gains of the second group of EDFAs are adjusted to guarantee that the input power levels of PL3 are the same for the three tributaries. The purpose of achieving the same power level at the output of three SM tributaries is to make the gain/loss condition of each tributary as close as possible, satisfying the condition $\eta_1 = \eta_2 = \cdots = \eta_N$ discussed in section 2. Note that the propagation length of the three tributaries from PL2 to PL3 must be equal to facilitate MIMO processing. Therefore, additional SMFs are added to TA and TB (not shown in Fig. 4) to precisely match the length of each tributaries by checking their propagation delay using a digital oscilloscope. The three converted signals are then connected to the input ports of PL3 and converted back to an MDM superchannel at the converted wavelength. The converted/dropped/added MDM superchannels are further converted to SM signals by PL4 and received by three polarization-diversity coherent receivers. A total of 12 high-speed digital signals are obtained by sampling the outputs of the coherent receivers at 50 GS/s using three synchronized high-speed digital oscilloscopes (Tektronix, two with 33 GHz ADC bandwidth and one with 20 GHz bandwidth). The received digital signals are processed offline by a $6 \times 6$ MIMO algorithm for BER measurement. The offline digital signal processing includes: 1) time and frequency offset compensation; 2) channel estimation and compensation; 3) phase noise compensation; 4) BER calculation. The spectral inversion due to FWM has been taken into account. Every BER point is evaluated over 1 million bits.
5. System characterizations

5.1 Optical spectra

The optical spectrum at the output of SOA-A is shown in Fig. 5(a). As a proof of concept demonstration, the separation between the pumps and signal are quite small since the bandwidth of the input signal is not demanding, resulting in many FWM peaks generated around the target idler. It is possible to move the undesired FWM frequencies further away from the converted signal by increasing the separation between the two pumps or the separation between the signal and pump 2. The spectra at the output of SOA-B and SOA-C are similar except for a power difference of the idler of a few dB since the CEs of SOA-B and SOA-C are lower than that of SOA-A, as shown in Fig. 2. The optical spectrum at the TA input of PL3 is shown when the converted and added signals are both present by the blue solid line in Fig. 5(b). The spectrum of TC in this case is similar. However, the spectrum of TB is much noisier as shown by red-dashed line in Fig. 5(b) because EDFA5 used in TB has a relatively larger noise figure (NF) compared to other EDFA4 and EDFA6. The NF of EDFA5 is 19 dB, significantly higher than that of the other two EDFAs, which is 4.1 dB and 5 dB, respectively. The input signal and pump powers are $-3$ dBm and 8 dBm (total pump powers), respectively. Note that the absolute power levels shown in Fig. 5 depend on the attenuation added to the signal that is sent into the OSA. The input power to EDFA1-3, which includes the pump and signal light, is about 10 dBm, and the converted idler signal which has passed the WSS is about $-15$ dBm before EDFA4-6. The resolution of the OSA is 0.02 nm. Note that throughout the paper, noise power has been integrated over 0.1 nm to calculate OSNR.

![Optical spectrum at the output of SOA-A.](image1)

![Optical spectrum at the input TA (blue solid line) and TB (red dashed line) of PL3.](image2)

5.2 Optimization of input signal and pump power to the SOAs

As discussed in section 3, the CE of the FWM process is sensitive to the input signal and pump powers of the SOAs. In this section, we carry out detailed analysis to optimize the signal/pump power levels at the input of the SOAs according to the BER performance evaluations. In the following, we set the power condition to be identical for the three SM tributaries. First, the total pump input power is fixed at 8.2 dBm. The BER performance as a function of signal power at the input of the SOAs is shown by the red line with star symbols in Fig. 6(a). In this case, the optimum signal power is $-6$ dBm with BER values between $10^{-4}$ and $10^{-5}$. The existence of an optimum signal power can be explained as follows. When the signal power is low, the increase of signal power helps to increase the OSNR of the converted signal, resulting in BER improvement. However, the BER degrades quickly as the signal
power increases beyond the optimum value due to intensity and phase noise transferred from the pumps through pump-signal interactions by cross-gain modulation (XGM) and cross-phase modulation (XPM) in the SOAs. Therefore, there is a trade-off between pump-transferred noise and OSNR. Note that the gain saturation effect helps reducing the detrimental effects induced by XGM and XPM [33]. This has been verified by increasing the pump power from 8.2 dBm to 9.5 dBm as shown by the blue line with filled circles in Fig. 6(a). In such case the minimum average BER drops to $10^{-5}$. The corresponding optimum signal power also increases from $-6$ dBm to about $-3.4$ dBm. We further investigate the impact of pump power while keeping the signal power at $-3.4$ dBm, as shown in Fig. 6(b). In this case, the BER drops continuously as the pump power increases, indicating that a better performance is achieved in the deep gain saturation regime. Further increase of the pump power is prohibited by the maximum power ratings of the SOAs.

![Fig. 6. Optimization of the signal and pump power levels at the input of the SOAs. (a) Measured BER as a function of signal power while keeping the total input pump power at 8.2 dBm (red-star line) and 9.5 dBm (blue line with filled circles). (b) Measured BER as a function of pump power while keeping the signal power at $-3.4$ dBm (identical for all tributaries). Pump conditions are identical for all tributaries.](image)

5.3 Impact of SM signal power and OSNR imbalance

As discussed in section 2, the imbalance of signal power between the three SM tributaries plays a similar role as mode-dependent loss (MDL). It has been verified that the signal power levels at the output of PL2 are the same for the three tributaries. Thus the input power of PL3 should be the same for the three channels. By varying the gain of the second group of EDFAs shown in Fig. 4, the impact of signal power imbalance between the different tributaries can be analyzed. The signal power of TA is varied intentionally while preserving the signal power of TB and TC and the resulting BER of the received signal is shown in Fig. 7(a). Our measurement shows that the BER performance is surprisingly robust to the variation of power imbalance. BER below $10^{-4}$ can be achieved for power variations of more than 10 dB. Since the polarization dependent operation of the SM-WCs is eventually converted to the MDL of the scheme by PL3 and PL4 (shown in Fig. 4), conclusion may also be drawn that the scheme is robust to the polarization dependent operation of the SM-WCs. The impact of the MDL of the PLs may be considered similarly.

In addition, we investigated the impact of OSNR imbalance by varying the OSNR of TA while keeping the OSNR of TB and TC at 18.9 dB and 19.7 dB, respectively. Noise power has been integrated over 0.1nm to calculate OSNR. For this measurement the signal power of each tributaries at the input of PL3 is fixed at 0 dBm. The OSNR is measured at the input of PL3 and changed by tuning the SOA current since the CE of FWM decreases as the SOA bias current decreases, resulting in a lower OSNR for a given total output power of the following
EDFA. Unlike power imbalance, it is found that the BER performance keeps improving as the OSNR of TA increases. This may be explained by the fact that the increase of OSNR of one of the channels gradually improves the overall OSNR of the MDM superchannel towards the BER floor set by the OSNRs of the other two tributaries.

![Fig. 7. Impact of signal power and OSNR imbalance among three tributaries at the input of PL3. (a) BER as a function of signal power of TA while keeping the power of TB and TC at 0 dBm. (b) BER as a function of OSNR of the signal of TA while the OSNR values of TB and TC are 18.9 dB and 19.7 dB, respectively. The OSNR of TA is varied by changing the current of SOA-A. The signal power levels of all tributaries are set to 0 dBm in this case.]

6. Wavelength conversion performance of a six-mode MDM superchannel

The BER performance of WC of an MDM-PDM-OFDM QPSK signal is carried out first. The averaged BER performance over six modes of the converted as well as added MDM superchannel as a function of OSNR averaged over three SM tributaries is shown in Fig. 8. The OSNR of three SM tributaries are set to similar values by tuning the current of the SOAs simultaneously. Each BER point is averaged over three measurements. Two different reference back-to-back measurements are carried out for comparison. That is, connecting PL1 to PL4 directly (2-PL b2b) and PL2 to PL3 directly (4-PL b2b), where the first scenario corresponds to the BER performance of the drop MDM superchannel. It is found that the converted signal has about 2.8 dB and 2.5 dB OSNR penalty compared to the 2-PL b2b case and the 4-PL b2b case, respectively, evaluated at the forward error correction (FEC) hard limit (BER of $3.8 \times 10^{-3}$). To measure the BER performance of the added channel, the OSNR of the added channels is varied by tuning the attenuator after the PBS in the Tx (not shown in Fig. 4) and the noise loading is performed by the second group of EDFAs. The added channel performance is similar to that of the converted signal in general and is slightly better than that of the converted signal at a BER of $3.8 \times 10^{-3}$. The OSNR penalty for the added channel is believed to be caused by the bad performance of EDFA5. As discussed in section 5.1, the NF of EDFA5 is significantly higher than the other two, indicating that EDFA5 is not working properly which may introduce signal distortion apart from OSNR degradation. Since the converted signal is also amplified by this EDFA, the OSNR penalty measured for the converted signal may also be partly attributed to the poor behavior of EDFA5. Comparing the BER performance of the converted and the added signal, the signal degradation introduced by the AOWC processing unit composed of three SOAs is about 0.5 dB in the case of an OFDM-QPSK signal.
Compared to QPSK signals, AOWC of a 16-QAM signal requires a higher OSNR of the converted signal and less intensity and phase noise transfer from the pump. This can be achieved by increasing the SOA current from 210 mA to 280 mA. The BER measurement of the 16-QAM signal is carried out in this case (other conditions are the same as for QPSK measurements) and the results are shown in Fig. 9. All six modes can be converted at a BER below soft decision (SD) FEC limit (BER of $1.98 \times 10^{-2}$), and the average BER could reach below the hard-decision FEC limit. Better results could be expected by further increasing the OSNR of the converted signals as well as reducing the transferred phase noise simultaneously, for instance by increasing the bias current of the SOAs. However, this is again limited by the maximum ratings of the devices used in this proof-of-concept work.

**7. Conclusion**

Encouraged by the idea of utilizing well-developed SM techniques in multimode systems by multimode-SM-multimode conversion in astrophotonics, we report the first AOWC of an MDM superchannel consisting of $2^N$ modes by following a similar procedure. Conversions from multimode to SM and back are realized by PLs instead of conventional MMUXs,
avoiding mode combining loss that scale exponentially with $N$. When signals are in SM status, coherent wavelength conversions are performed by using cross-polarized dual-pump FWM in $N$ SOAs. AOWCs in SM-NEs is a black box operation with respect to mode profiles since all modes actually see identical WC conditions. The data integrity of the converted MDM superchannel has been verified by using coherent detection and DSP. To show that the scheme is also transparent to data format and polarization, as well as compatible with multi-carrier signals, PDM-OFDM-QPSK/16-QAM is used in this work. Bit error rate below the FEc hard limit ($3.8 \times 10^{-3}$) has been achieved for QPSK format at a net bitrate of 104.2 Gbit/s with 2.5 dB OSNR penalty compared to the back-to-back case. BER below the soft decision FEc threshold ($1.98 \times 10^{-2}$) has been achieved when the signal is modulated with the 16-QAM format, giving a total net aggregate bit rate of 185.8 Gb/s by taking 20% coding overhead into account. Add and drop functionalities that are important for ROADMs have also been demonstrated for an MDM superchannel with the added channel showing similar OSNR penalty as the wavelength converted signal, indicating that the penalty induced by the $N$ SE-AOWC units is actually quite small. The working conditions of the SOAs including pump and signal power levels prove to be critical for the quality of the converted signal. Better results are achieved by deeply saturating the SOAs since it effectively reduces the intensity and phase noise transfer from the pump to the converted signal due to XGM/XPM between the original superchannel and the pumps. It has been found that optimum results are achieved by choosing a good trade-off between the OSNR of the converted signal and pump-transferred noise. We have also shown that the scheme can tolerate more than 10 dB CE imbalance between the SM-AOWCs. We believe this work opens a promising way to perform all-optical signal processing for MDM superchannels.

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