Polarization-insensitive Ultra-Selective Add and Drop Multiplexer Using Rectangular Brillouin-based Filters

Wei Wei[1,2], Lilin Yi[2], Yves Jaouën[1], Michel Morvan [3],Weisheng Hu[2]

[1] Institut Mines-Télécom, Télécom ParisTech, Paris, France, yves.jaouen@telecom-paristech.fr
[2] State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China, lilinyi@sjtu.edu.cn
[3] Institut Mines-Télécom, Télécom Bretagne, CNRS UMR 3192, Technopôle Brest-Iroise, France

Abstract *Ultra-selective separation-aggregation operation using polarization-insensitive rectangular optical filters based on stimulated Brillouin scattering in optical fibre has been realized. Extracting a ~2-GHz dual-polarization OFDM signal from an ultra-dense multiplex with ~300-MHz guard-band shows only ~1-dB penalty for QPSK format.*

Introduction

The concept of "flex-grid networking" has emerged as a key requirement for tomorrow's flexible and dynamic networks. In this context, super-channel approaches, such as Nyquist-WDM and multi-band orthogonal-frequency-division-multiplexing (MB-OFDM) signals, allow both high spectral efficiency, small guard-band and all-optical sub-band switching, which make them promising candidates for 400 Gbps and 1 Tbps long-haul WDM transmission[1]. The signal extraction-aggregation requires a very high-resolution frequency selectivity and makes high-precision filters the most important component in reconfigurable optical add and drop multiplexer (ROADM)[2].

The current state-of-art in small-grid flexible ROADM is based on arrayed-waveguide grating and liquid crystal on silica (LCoS) technique[3]. It can reach ~0.8 GHz resolution and ~GHz bandwidth. However the in-band filter shape is not flat and shows a large roll-off, which both induce signal distortions and require larger guard-bands. For implementing GHz-bandwidth rectangular filter, stimulated Brillouin scattering (SBS) has been considered as a promising technique with inherent flexibility[4]. Based on SBS effect in fibre with a precise feedback control, we have realized a bandwidth-tunable narrowband rectangular optical filter[5], and demonstrated a SBS-based ROADM structure[6]. Due to the SBS polarization dependent gain and loss, the ROADM was only capable of processing single-polarization OFDM signal thus being incompatible with the current polarization-division-multiplexed (PDM) system and losing half of the capacity. Moreover, since the state of polarization (SOP) of the signal and the pump had to be precisely controlled to ensure the optimum efficiency, a lot of polarization controllers (PC) were needed therefore increasing system complexity and limiting the SBS-based ROADM to only "proof-of-concept".

In this paper, we present for the first time an ultra-selective ROADM for PDM MB-OFDM signal deploying polarization-insensitive rectangular filters based on SBS effect. The polarization-independent rectangular Brillouin gain and loss are achieved by using well-controlled depolarized frequency-sweeping pump. Optical separation and aggregation are demonstrated with a 3-band PDM OFDM signal in QPSK format. Thanks to the narrow passband and the steep edges of the proposed filters, the bandwidth of each OFDM band can be set to 2 GHz with guard-bands of ~300 MHz. The filter induced total penalty is only ~1 dB at bit error rate (BER) of 10^{-3} benefiting from the uniform gain and loss in both polarization states.

Principles

As an essential technique, the Brillouin pump depolarizing process is shown in Fig. 1. First we use an optical single-frequency sweeping signal as the pump, which is modulated by an electrical sweeping signal from an arbitrary waveform generator (AWG). As long as the propagation time through the fibre is longer than the duration of the sweeping cycle, the pump can be considered as a broadband pump[4]. Then the pump wave passes through a polarization beam splitter (PBS) and is separated along two orthogonal polarization states. After time delay to induce fields decorrelation, the two branches are combined using a polarization beam combiner (PBC). Since there is only a single frequency existing at any specific time for each polarization state and the signal frequency on the two polarization projections are different at all times, the sweeping pumps along the two

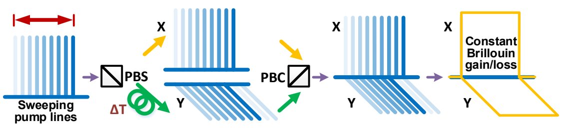

Fig. 1: The Principle of achieving polarization-independent SBS by using depolarized frequency-sweeping pump.

polarization states are independent. Thus, the pump can be considered as a polarization-multiplexed pump. Therefore the Brillouin gain and loss are both polarization-insensitive. As shown in Fig. 2, after only 5-10 iterations of the precise feedback control of the pump shape, we obtain a long-term stable 2-GHz wide rectangular Brillouin filter. No matter how we change the SOP of the probe signal, the filter shape is constant keeping a fixed and smooth phase response, which proves the validity of the pump depolarization process.

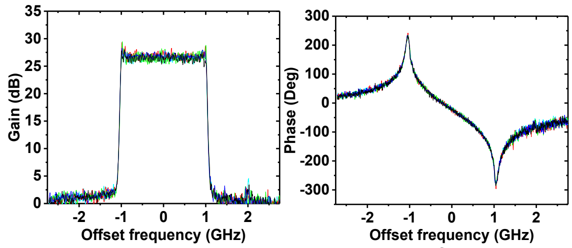

Fig. 2: The amplitude and phase responses of the proposed Brillouin filter with different SOP of the probe.

Once the polarization-insensitive rectangular filter has been achieved, the ultra-selective PDM ROADM can be implemented. The flexible-grid ROADM structure is shown in Fig. 3. An SBS gain filter (bandpass) selects the desired band to realize drop function meanwhile an SBS loss filter (stop-band) removes the unwanted band in MB-OFDM signal for another signal to add in. Thanks to the polarization-insensitive SBS gain and loss, the ROADM is capable of handling PDM signal. Since no PCs are required for adjusting the signal SOP, the system structure is simplified to a great extent. Meanwhile, the guard-band between different signal bands can be set very small benefiting from the rectangular filter shape. Besides the filter central wavelength and bandwidth tunability ensures flexible and high precision control of the proposed ROADM.

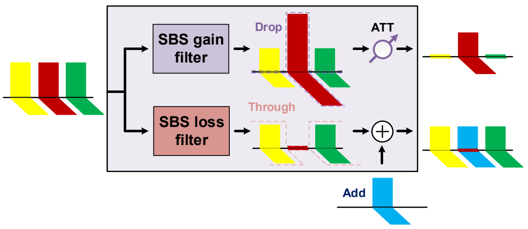

Fig. 3: Concept of the SBS-based PDM ROADM.

Experiment and results

The PDM ROADM experimental setup shown in Fig. 4 consists of three parts: the transmitter, the SBS based ROADM structure and the coherent receiver. In the transmitter part, the light from an external cavity laser (ECL) and 2 distributed feedback lasers (DFB) operating at ~1543 nm are modulated by the electrical OFDM signal satisfying the Hermitian symmetry from a Tektronix7221B AWG. Given the instability of the 3 lasers, the minimum guard-band of the 3 bands is set to 300 MHz. For each sub-band, 128 subcarriers are used in order to mitigate the effect of the ECL phase noise of ~100 KHz. Note that phase noise induces significant SNR penalties for 16-QAM, we use QPSK format for each subcarrier at the sampling rate of 2.5 GS/s. The bandwidth is set to 2 GHz by adjusting the number of empty subcarriers. A polarization multiplexer with 1-symbol delay is used for PDM signal generation. Then the 3-band PDM OFDM signal passes through a polarization scrambler (PS) to emulate the polarization variations over the transmission link and is then split into 2 parts. The central bands are absorbed or amplified by 2.1-GHz rectangular dual-stage SBS filters with ~25-dB polarization-insensitive gain or loss in the separate branch respectively. The amplification or absorption occurs in 2 cascaded 25-km fibre sections without any polarization control. After passing through a 12.5-km long fibre for decorrelation, the amplified central band is reinserted in the multiplex with the same power level ensured by a variable optical attenuator (VOA) in the gain branch and a mid-stage EDFA in the loss branch. In the receiver part, the signal from the ROADM is adjusted to the optimal power and a broadband ASE noise source is added for the BER vs. SNR measurements. Finally the OFDM signal is detected by a coherent receiver followed by a high-speed real time oscilloscope. The OFDM signal is then decoded by off-line processing.

As to the depolarized SBS pump generation, we use the second AWG output to generate a 2.1-GHz wide electrical sweeping signal with precise control and modulates the light from 2 DFB lasers. An I&Q modulator (IQM) is used to

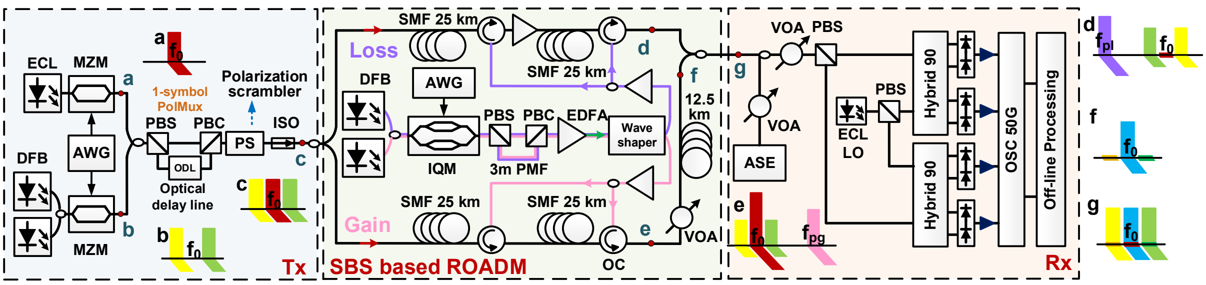

Fig. 4: Experimental setup and the optical spectrum schemes at different points.

realize optical carrier suppressed single-sideband modulation for SBS gain and loss pump generation. Then the broadband pump is depolarized by a PBS, a PBC and a 3-meter polarization maintaining fibre (PMF). After pre-amplification, the 2 pump waves with around 22-GHz frequency spacing are separated by a Finisar waveshaper and boosted to a higher level acting as the pump. Note that the waveshaper is not required if another IQM is used for gain/loss pump generation.

In order to further prove the feasibility of the proposed ROADM. We evaluate the ROADM performance by BER-SNR measurements. First we compare the single band amplification with single-polarization pump and polarization-multiplexed pump. As shown in Fig. 5(a), the single-polarization pump induced penalties are ~6 dB and 2.5 dB for X and Y polarization states respectively. The penalty for each polarization is remarkable and unpredictable due to the polarization-dependent SBS gain. While using the polarization-multiplexed pump, the SNR penalties are only ~1 dB at BER of 10^{-3} respectively. The constellation diagrams obtained when no ASE noise is added also illustrate the signal quality difference obviously. Note that the SNR difference between X and Y polarizations without SBS gain results from a ~1dB PDL of the used PDM emulator. Then we add the amplified band back to the central absorbed notch as shown in Fig. 5(b). The electrical spectra in the insets illustrate obvious

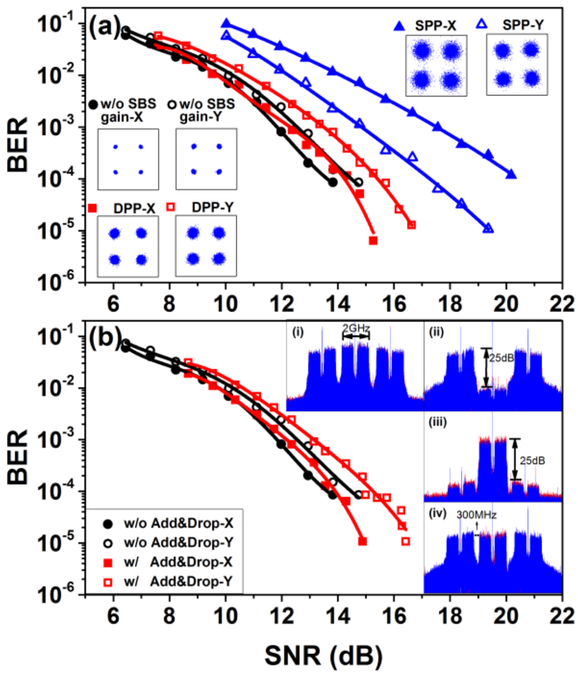

Fig. 5: System performance of (a) Single band amplification (b) Full ROADM. Insets: (i) original signal (ii) absorbed central band (iii) amplified central band (iv) final add & drop spectra in both polarization states. SPP: single-polarization pump, DPP: dual-polarization pump.

precise amplification and complete absorption in both polarization states. The spectra before and after the add-and-drop process look almost the same. The penalties are still within 1 dB for both X and Y polarizations, which imply that there is no extra penalty at all for adding a sub-band back.

Conclusions

We have presented an ultra-selective ROADM for PDM MB-OFDM signal with 2-GHz spectral granularity and 300-MHz guard-bands deploying polarization-insensitive rectangular filters based on SBS effect for the first time. By using well-controlled depolarized frequency-sweeping pump, we solve the issue of polarization-dependent SBS gain/loss and obtain polarization-insensitive rectangular SBS filters. Optical separation and aggregation are demonstrated with a 3-band PDM OFDM signal in QPSK format. The filter induced total penalty is only ~1 dB benefiting from the uniform gain and loss in both polarization states. With no PCs and reduced system complexity, the SBS-based PDM ROADM is more applicable for practical implementation and the superiority of the rectangular filter shape and flexibility is taken to the extreme.

Acknowledgements

This work was supported by National Basic Research Program of China (2012CB315602), National Natural Science Foundation of China (61322507 and 61132004), Program of Excellent PhD in China (201155) and "Futur et Ruptures" program from Institut Mines Telecom in France.

References

[1] A. Lord et al., “Core networks in the flexgrid era,” J. Lightwave Technol., Vol. **33**, no. 5, p. 1126 (2015).

[2] E. Pincemin et al., “Multi-band OFDM transmission at 100 Gbps with sub-band optical switching,” J. Lightwave Technol., Vol. **32**, no. 12, p. 2202 (2014).

[3] R. Rudnick, et al., “Sub-banded / single-sub-carrier drop-demux and flexible spectral shaping with a fine resolution photonic processor,” Proc. ECOC, PD4.1, Cannes (2014).

[4] Y. Stern et al., “Tunable sharp and highly selective microwave-photonic band-pass filters based on stimulated Brillouin scattering,” Photon. Res. Vol. **2**, no. 4, p. 18 (2014).

[5] Lilin Yi et al., “High selectivity, ideal rectangular microwave photonic filter based on stimulated Brillouin scattering,” Proc. OFC, Tu3F.5, Los Angeles (2015).

[6] W. Wei et al., “Ultra-selective flexible add-drop multiplexer using rectangular stimulated Brillouin scattering filters,” Proc. OFC, Tu3D.1, Los Angeles (2015).