

# Ultra-Selective Flexible Add-Drop Multiplexer Using Rectangular Stimulated Brillouin Scattering Filters

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**Abstract:** We demonstrate optical separation-aggregation of a ~2-GHz sub-band for a multi-band OFDM signal in QPSK and 16-QAM formats. The band gap is 300-MHz by using a rectangular optical filter based on stimulated Brillouin scattering.

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## 1. Introduction

The reconfigurable optical add/drop multiplexer (ROADM) is an important function in an optical network. As a promising technique, multi-band orthogonal frequency division multiplexing (MB-OFDM) has many advantages including high spectral efficiency, anti-interference and flexible sub-band aggregation and multiplexing capability [1]. When MB-OFDM signals are transmitted through the ROADM, the switching flexibility is limited by the ROADM resolution which is determined by the internal filtering technology. Moreover, the overall efficiency is decreased due to the usage of guard band gaps [2]. To maintain both OFDM flexibility and spectral efficiency, a reconfigurable narrowband rectangular optical filter is the ideal component for ROADM.

In this paper, we demonstrate a ROADM solution with GHz spectral granularity. We have validated this approach for a 3 sub-band OFDM signal in QPSK and 16-QAM formats. For the proof of concept, we have limited the demonstration to a single polarization MB-OFDM signal. The bandwidth of each sub-band signal is only 2-GHz and the net bit-rate is ~5 Gbit/s using 16-QAM modulation format. We use a dual-stage band-pass and stop-band optical filter based on stimulated Brillouin scattering (SBS) in optical fiber to realize add and drop functions at the same time. Compared to widely-used commercial filters employing tunable bulk-grating [2], liquid-crystal on silicon (LCOS) technique [3] or the recently proposed arrayed-waveguide grating [4], our proposed SBS filters have rectangular response and adjustable bandwidth from 100 MHz to 3 GHz. Experimental results show that the SNR penalty induced by the SBS add/drop filter is only less than 2 dB at BER of  $10^{-3}$ .

## 2. Principle

In a ROADM, a band-pass filter only keeps the desired sub-band to realize the drop function meanwhile a stop-band filter removes the sub-band in the MB-OFDM signal to reattribute the spectral band to another sub-band signal as shown in Fig. 1(a). So the ROADM resolution and flexibility are determined by band-pass and stop-band filter properties. Ideally, a flexible narrowband rectangular optical filter is required.

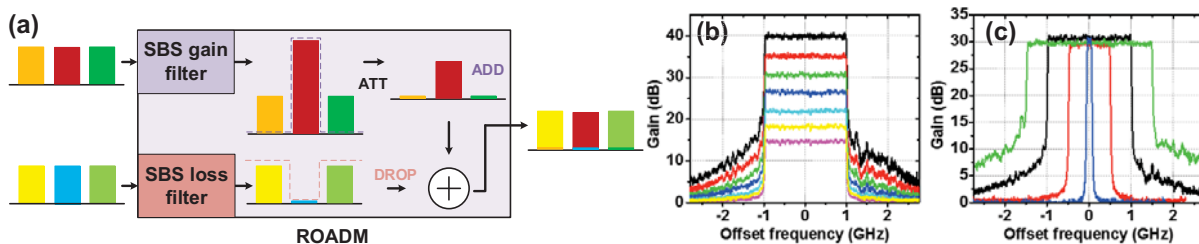


Fig. 1. (a) Concept of the SBS-based ROADM, (b) SBS gain filter with reconfigurable selectivity, (c) SBS gain filter with flexible bandwidth.

In the previous work [5], we have proposed an SBS-based rectangular optical filter. The proposed filter has its inherent advantages such as narrowband and high flexibility of both bandwidth and central wavelength. It can operate both as a gain and a loss filter by properly setting the pump wavelength which is desirable for the ROADM application. The SBS-based rectangular filter is generated as follows. First, we use an arbitrary waveform generator (AWG) to generate an electrical comb which then modulates a CW light to shape the appropriate pump wave. A feedback compensation algorithm is proposed to digitally control the shape of the targeted SBS filter response. Nonlinearity management is used to improve the passband flatness. In this paper, we use dual-stage amplification

and absorption to further increase the filter selectivity. By all these means, we obtain a high selectivity narrowband filter with nearly perfect rectangular profile. Figure 1(b) illustrates a group of filters with 2 GHz bandwidth and different gains. The filter tunability from 100 MHz to 3 GHz is shown in Fig. 1(c), which enables the flexibility of proposed ROADM architecture.

### 3. Experiment and results

The OFDM experimental setup consists of three parts: the transmitter, the SBS based ROADM itself and the coherent receiver as shown in Fig. 2. In the transmitter part, the light from an external cavity laser (ECL) and 2 distributed feedback lasers (DFB) operating at  $\sim 1543$  nm are modulated by the electrical OFDM signal. As only a single output of the Tektronix7221B AWG is available for OFDM signal generation, an OFDM signal satisfying the Hermitian symmetry is generated. This constraint does not affect our analysis as all subcarriers are treated independently at the receiver side. Given the instability of the 3 lasers, the minimum band gap of the 3 sub-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  $\sim 100$  KHz. Both QPSK and 16-QAM modulation formats are employed for each subcarrier at the sampling rate of 2.5GSamples/s. The bandwidth is set to 2 GHz by adjusting the number of empty subcarriers. After passing through an isolator (ISO) to block inverse pump light, the single polarization 3 sub-band signal is split into 2 parts: the upper (lower) path, and the central band is absorbed (amplified) by a 2.2-GHz rectangular dual-stage SBS gain (loss) filter. The extra 200 MHz is dedicated to laser drift mitigation. After passing through a 12.5-km long fiber, the amplified central band in the upper path is de-correlated with the 2 side bands in the lower path. Then the 3 bands are combined together with the same polarization state adjusted by using 2 polarization controllers (PCs). The signal from the ROADM is adjusted to the optimal power and a broadband ASE noise source is added for the SNR-BER measurement. Finally the OFDM signal is detected by an intradyne coherent receiver followed by a high-speed real time oscilloscope. QPSK and 16-QAM constellations are then obtained by off-line processing. A more precise description of OFDM signal generation and detection is in [2, 6].

Concerning the SBS pump generation, we use the second AWG output to generate a 2.2-GHz wide electrical signal that modulates the light from 2 DFB lasers. The amplitude of the electrical comb is well controlled using a feedback compensation algorithm. An I&Q modulator (IQM) is used to realize optical carrier suppressed single-sideband modulation for SBS gain and loss pump generation. After pre-amplification, the 2 pump waves with around 22-GHz frequency spacing are separated by a 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 each stage, a PC is used to maintain the SBS gain or loss at the maximum value through 25-km long fiber. An EDFA after the first loss filter stage and an attenuator after the second gain filter are used to maintain the 3 sub-bands at the same power level.

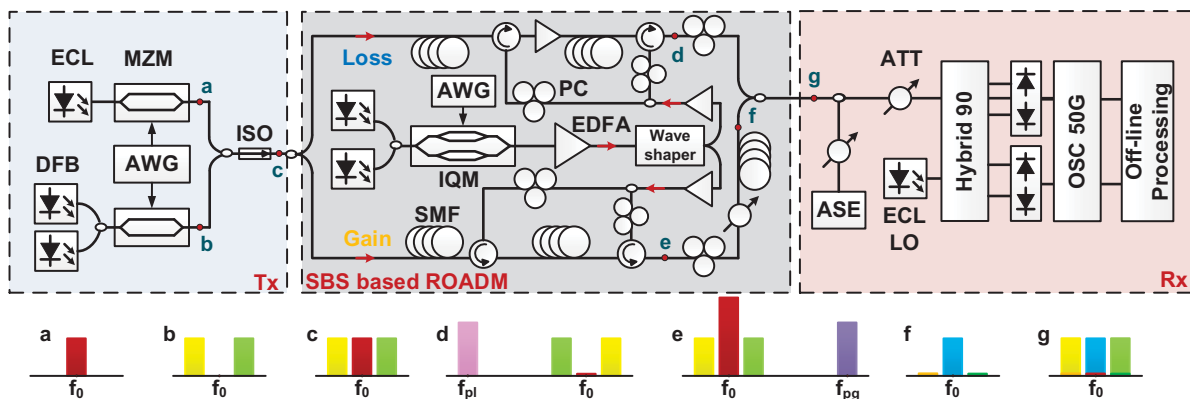


Fig. 2. Experimental setup and the optical spectrum schemes at different points

Firstly the validity of the SBS amplification with different gains for OFDM signal has been assessed. Figure 3(a) shows the electrical spectrum of the received original 3-band OFDM signal and Fig. 3(b) illustrates the spectrum when the central band is amplified by the SBS gain filter. The SNR-BER curves for the QPSK format are presented in Fig. 3(c) while the 16-QAM case in Fig. 3(d). Different constellation diagrams are also given in the insets. After being amplified by the SBS gain filter with 25-dB gain, the SNR penalties are only  $\sim 0.5$  dB and  $\sim 2$  dB at a BER of  $10^{-3}$  for QPSK and 16-QAM respectively. For 16-QAM, larger penalty has been observed when the SNR is high in large gain cases because of the large SBS-ASE noise. The result has proved that the SBS gain induced penalty is not significant especially when the signal format is QPSK. It also validates the feasibility of the proposed rectangular SBS gain filter in the OFDM system.

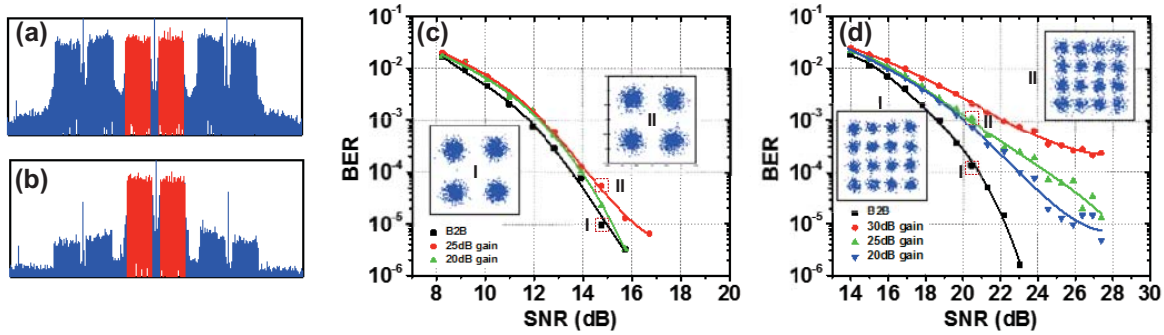


Fig. 3. Amplified OFDM signals: (a) Original 3 sub-bands OFDM signal (b) Amplified central band by using the SBS gain filter (c) BER-SNR performance for QPSK (d) BER-SNR performance for 16-QAM

Once the standalone filter concept is proved, the performance of the full add/drop function is measured. Figure 4(a) shows the electrical spectrum of the absorbed central band. The SBS loss is  $\sim 23$  dB corresponding to a pump power of 24 dBm and the gain pump power is set to  $\sim 22.3$  dBm to achieve 25-dB gain. Figure 4(b) illustrates the spectrum when the amplified central sub-band is added at the position of the notch. To ensure the added central band and two sidebands with the same power, the 23-dB SBS loss corresponds to the in-band crosstalk of the central band. The BER performance is shown in Fig. 4. When the band gap is reduced from 1 GHz to 300 MHz, the performance difference is negligible. Thanks to the sharp rectangular response of the SBS filter, it is even possible to narrow the band gap as low as 100 MHz, but due to the limitation from the laser stability, we only set the minimum band gap to 300 MHz. Moreover the SNR-BER curves for the QPSK format indicate that there is no obvious penalty induced by the add/drop function. But for 16-QAM signal,  $\sim 2$  dB extra penalty is observed from Fig. 4(d) due to residual in-band crosstalk. When the pump power of the SBS loss filter is reduced, the residual central band induces more severe crosstalk to the added central band. As shown in Fig. 4(c) and 4(d), when the in-band crosstalk is  $\sim 15$  dB, the penalty for QPSK signal at BER of  $10^{-3}$  is increased to  $\sim 1.5$  dB while the BER performance is dramatically degraded for 16-QAM. Since the SBS gain corresponds to the in-band crosstalk of the two side OFDM-bands, 25-dB SBS gain and loss can achieve good add/drop performance for both central and side OFDM-bands even for 16-QAM format.

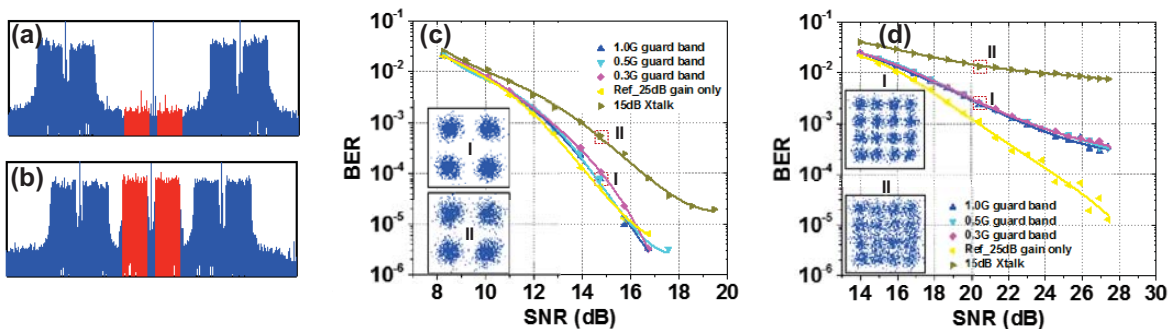


Fig 4. Add & Drop performance: (a) The spectrum of absorbed central band, (b) Another amplified sub-band added in the notch position, (c) BER-SNR performance for QPSK, (d) BER-SNR performance for 16-QAM.

#### 4. Conclusion

We have demonstrated an ultra-selective flexible add-drop multiplexer for MB-OFDM signal sub-band switching in QPSK and 16-QAM formats. Thanks to the dual-stage SBS narrowband rectangular filter, the band gap can be set as narrow as 300 MHz to ensure high spectral efficiency. Meanwhile, the flexibility of the OFDM is taken to the extreme with the help of the filter bandwidth flexibility. Only small penalties are induced by the SBS ASE noise and crosstalk which prove the feasibility of the SBS amplification and absorption in OFDM transmission and networks. Future work is planned to extend the concept of ultra-selective flexible add-drop multiplexer to dual polarization MB-OFDM signal using polarization insensitive SBS filters.

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