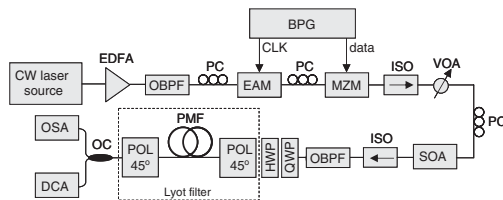


# Semiconductor optical amplifier pattern effect suppression using Lyot filter

K.E. Zoiros, C. O'Riordan and M.J. Connelly

The feasibility of employing a Lyot filter to compensate for the pattern effect in a semiconductor optical amplifier (SOA) is experimentally demonstrated. The operation mechanism relies on the control of its comb-like transfer function by proper adjustment of the wavelength spacing and detuning to suppress the spectral components broadened owing to SOA gain saturation. The scheme is experimentally demonstrated on amplified 10 Gbit/s return to zero data.

**Introduction:** Semiconductor optical amplifiers (SOAs) have become a key technology for the development of lightwave communications and networks enabled by their ultra-wide bandwidth, low power consumption, compactness and ability for integration [1]. Nevertheless, in direct signal amplification applications the combination of the power and the duration of the input signal pulses can be such that the SOA is driven into intense saturation and cannot fully recover its gain until its next excitation. If a random data stream is launched into the SOA, the resulting gain saturation and finite recovery time results in an amplified output that is not uniform, leading to degradation in system performance [2]. One solution that has been proposed to resolve this problem relies on the fact that the strong gain saturation also induces self-phase modulation (SPM), resulting in broadening of the pulse spectrum [3]. If the unwanted frequency-shifted components are appropriately suppressed then the pattern-dependent distortion on the amplified data stream can be cancelled as reported in [4–6]. In this Letter we propose to implement this technique using a Lyot filter [7] to greatly reduce the pattern effect on a 10 Gbit/s return-to-zero (RZ) data pulse stream amplified by an SOA. Such Lyot filters have previously only been used for signal processing [8] and in multi-wavelength lasers [9]. Owing to the Lyot filter's low cost, relatively simple construction, periodic transfer function, good peak-to-notch contrast ratio, reasonable insertion loss, operational stability and flexible tunability it can be an efficient alternative option to existing schemes [4–6].



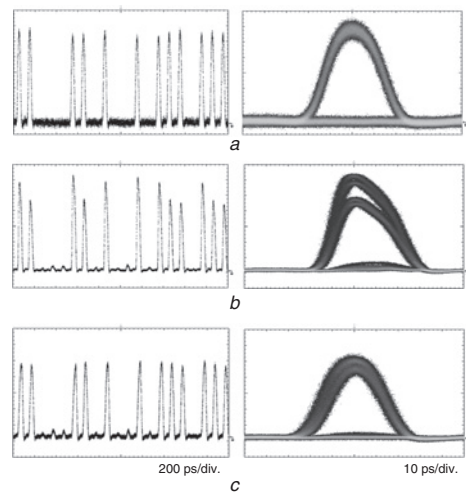
**Fig. 1** Experimental setup

EDFA: erbium-doped fibre amplifier, OBPF: optical bandpass filter, PC: polarisation controller, BPG: bit pattern generator, EAM: electroabsorption modulator, MZM: Mach-Zehnder modulator, ISO: isolator, VOA: variable optical attenuator, SOA: semiconductor optical amplifier, QWP: quarter wave plate, HWP: half wave plate, POL: polariser, PMF: polarisation-maintaining fibre, OC: optical coupler, DCA: digital communications analyser, OSA: optical spectrum analyser

**Experiment:** Fig. 1 illustrates the experimental setup for demonstrating the pattern effect induced on RZ pulses when amplified in an SOA and verifying the capability of the proposed scheme to suppress it. A 1550 nm tunable laser source is amplified by an erbium-doped fibre amplifier and subsequently modulated by an electroabsorption modulator (EAM) and a LiNbO<sub>3</sub> Mach-Zehnder modulator (MZM) driven by the internally synchronised clock (CLK) and data output of a bit pattern generator (BPG), respectively, to form a 10 Gbit/s RZ 2<sup>7</sup>–1 pseudorandom binary sequence (PRBS) having full-width at half-maximum (FWHM) pulsewidth of 27 ps. This signal is amplified by an SOA, which is a 1 mm-long, bulk InGaAsP/InP device (Kamelian, model OPA-20-N-C-FA) with a fibre-to-fibre small signal gain of 23 dB, gain polarisation dependence of 0.5 dB, saturation output power of 13 dBm and gain recovery time of about 75 ps at 1550 nm when biased at 270 mA and thermally stabilised at 20°C. The SOA input optical power is controlled by an optical attenuator (VOA). The SOA output is connected to the Lyot filter, which comprises a 5 m-long section of polarisation maintaining fibre (PMF) and polarisation mode group delay  $B = 1.3$  ps/m between two polarisers (POL) aligned at 45° with respect to its birefringent axes. Directly

before the first polariser, quarter and half wave plates (QWP, HWP) are inserted to ensure favourable alignment of the incoming modulated light's state-of-polarisation through the structure. The total loss inserted from all these components is about 8 dB. Where necessary across the whole configuration polarisation controllers (PC) are placed prior to polarisation-sensitive components to ensure best coupling of light, and optical bandpass filters (OBPF) are employed to reject the out-of-band noise, and isolators (ISO) are used to prevent undesirable back reflections.

**Results:** The average power level of the input signal to the SOA is set at –2 dBm, forcing it to operate in the heavily saturated regime. The time difference between the injected pulse repetition period and its FWHM is smaller than the SOA gain recovery time, which leads to significant pattern effects. Fig. 2 shows the experimental results obtained in the time domain using a digital communications analyser with 65 GHz optical bandwidth. For visual purposes, a representative 20 bit-long segment of 11000110100101110111 contained in the 10 Gbit/s RZ 2<sup>7</sup>–1 PRBS is used, which is illustrated in the left column of Fig. 2a. The logical '1's have an amplitude modulation (AM) of 0.35 dB [10], while the corresponding eye diagram in the right column has an extinction ratio (ER) of 20 dB. After the SOA alone, however, these features are not maintained owing to the pronounced pattern effect, which results in a poor performance observed in Fig. 2b. In fact, the marks suffer from severe amplitude fluctuations depending on whether they are preceded either by one or more spaces or other marks, as theoretically predicted in [10], resulting in an AM of 1.7 dB. Moreover, the eye diagram is degraded, since its shape is asymmetric, in accordance to [3] and comprises of sub-envelopes with its ER reduced below 10 dB. With the use of the Lyot filter, the pattern effect can be alleviated, as is evident in Fig. 2c where the peak variations of the '1's are balanced and the AM is restored to an acceptable value of 0.35 dB [10] while the eye diagram again becomes clear and open, having an ER of 17 dB. These improvements can be explained from the results in the frequency domain, which are shown in Fig. 3. The spectral response of the Lyot filter is shown in Fig. 3a. The important characteristic it exhibits is the cosine-squared periodic comb-like profile, with the null points situated midway between adjacent transmission peaks whose wavelength spacing or free spectral range (FSR) is approximately 1.2 nm. This finding agrees well with the theoretical value calculated from [7]  $FSR = \lambda_0^2 / (cBL)$  with  $\lambda_0 = 1550$  nm,  $c = 3 \times 10^8$  m/s and the parameter values of the employed PMF. The optical spectrum of the SOA input data signal is shown in Fig. 3b.

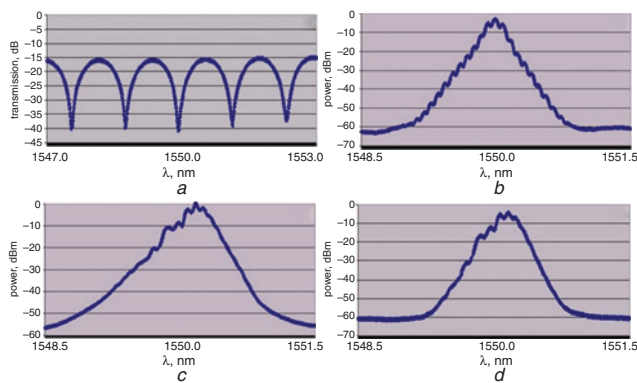


**Fig. 2** Temporal waveforms

a At SOA input  
b At SOA output  
c After Lyot filter  
Left column: PRBS sample of 20 bits. Right column: eye diagram

If the transmission peak of the filter is negatively detuned by a relatively small amount  $\Delta\lambda$ , with respect to the optical carrier, then the spectral components of the amplified pulses that have been shifted to longer wavelengths owing to SPM [3, 4], as shown in Fig. 3c, will be aligned

with the sharp notches of the Lyot filter response. The relative attenuation imposed by these notches is approximately 24 dB across the entire tuning range, thereby being attenuated in direct analogy to the degree of their shift. This can be done practically by choosing first the appropriate PMF length to adjust the FSR through a trial and error procedure that relies on the AM extent and the efficiency with which it must be reduced, and then rotating the wave plates to introduce the additional phase shift,  $\Delta\varphi$ , in order to vary  $\Delta\lambda$  up to 50% of the FSR according to  $\Delta\lambda = (\Delta\varphi/2\pi) \text{FSR}$  [7]. In this manner, the Lyot filter can suppress the red-shifted spectral components, as shown in Fig. 3d, and consequently the distortion in the profile of the amplified signal is removed, while the input power dynamic range is increased by an amount estimated according to the SOA characterisation data to be 5 dB. On the other hand, the price paid for the significant performance improvements achieved by its use is that the data sequence receives a peak amplification of about 2.5 dB less than after the SOA only. This happens because due to the filtering action a portion of information contained in the suppressed red-shifted spectral components is inevitably lost. Furthermore, the temperature dependence of the birefringence of the PMF causes a drift of the polarisation vector and subsequently a slow variation of the pattern amplitude so that during the experiment it was possible to achieve error-free operation for a very short time. However, this is not a fundamental problem but rather a technical difficulty that can be overcome with the commercially available technology, such as specialised PM photonic crystal fibres [11], which can enhance the stability of the scheme by making it less sensitive to changes in the environmental conditions. In comparison, there are other comb filter implementations with delay interferometers which are more robust to environmental perturbations, such as the birefringent fibre loop (BFL) [12] and the optical delay interferometer (ODI) [10]. The latter is also more compact and can be co-packaged with the SOA in a single module, which is more difficult to be done with the Lyot filter owing to its large physical size.



**Fig. 3 Measured optical spectra**

- a Lyot filter response
- b SOA input
- c SOA output
- d After Lyot filter

**Conclusion:** The capability of a Lyot birefringent comb filter to mitigate the pattern-dependent pulse distortion in a SOA employed in its classical amplification role has been experimentally demonstrated. The confirmed performance improvement suggests that this scheme can constitute a promising technological solution for combating the deleterious consequences of this effect.

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