7 Clark, M.V.: 'Adaptive frequency-domain equalisation and diversity combining for broadband wireless communications', *IEEE J. Sel. Areas Commun.*, 1998, **16**, (8), pp. 1385–1395
8 Ishihara, K., *et al.*: 'Comparison of SCFDE and OFDM with adaptive modulation and coding in nonlinear fading channel', *Electron. Lett.*, 2007, **43**, (3), pp. 174–175

High extinction switching of SOAs for in-band crosstalk reduction in PON

C. Antony, G. Talli, P.D. Townsend, J. Bauwelinck, D.W. Smith and I. Lealman

Burst-mode operation in next-generation large-split, long-reach 10 Gbit/s passive optical networks (PONs) poses challenging requirements on optical network unit (ONU) design. One critical requirement in high-split networks is to suppress the ONU off-state emissions sufficiently to prevent penalties arising from in-band crosstalk. Proposed and demonstrated is the use of semiconductor optical amplifiers (SOAs) to provide this high-extinction ONU gating function. A novel experimental technique for accurate characterisation of the dynamic extinction introduced by the SOAs is described, which is based on the bit error rate penalty induced by the interference from the SOA off-state emissions. The experimental results indicate that the proposed ONU design can allow the operation of PONs with 512-way splits.

Introduction: Multi-wavelength, long-reach (100 km) 10 Gbit/s passive optical networks (PONs) that integrate access and metropolitan area networks into a single, low-cost, all-optical system are promising candidates for future broadband access. The architecture enables a number of large-split, long-reach PONs, each working at different wavelengths to share the same backhaul fibre infrastructure using a dense wavelength division multiplexing (DWDM) wavelength plan. An example of such a network, which is currently being studied under the EU project PIEMAN, has 32 downstream and 32 upstream wavelengths on a 50 GHz grid in a pure C-band DWDM scheme and aims to support 512 customers per wavelength [1]. One of the major research challenges posed by these next generation PONs is the requirement for new 10 Gbit/s transmission technologies, which must operate in burst mode, in order to allow time-sharing of the available upstream bandwidth between customers using time division multiple access, and also be compatible with DWDM operation.

A key issue that arises from the burst-mode traffic in the upstream path of the PONs is the potential for interference between the active customer optical network units (ONUs) and the off-state emissions from the inactive ONUs at the same wavelength [2]. If the ONU off-state emission is not sufficiently suppressed, large interference penalties or even error floors can be generated at the upstream receiver. This sets a maximum limit on the aggregate off-state power, which is given by the sum of all off-state powers of the inactive users. To support a high number of users within a single network, which is desirable for economic reasons, each ONU is required to achieve extremely low power levels in the off-state. In the conventional gigabit PON (GPON) systems the ONU lasers are turned off between bursts using a fast switching of the bias and modulation current and a DC-coupled interface [3]. However, this approach poses great challenges in networks such as PIEMAN, which use DWDM, since rapid tuning and locking of the laser wavelength within the available 25 ns inter-burst guard bands is required. Hence alternative solutions are preferred in which the operating conditions of the lasers are maintained constant between bursts. This Letter introduces the concept of using high-extinction electro-optic switching of semiconductor optical amplifiers (SOAs) as a gating technique in the ONUs to reduce the effect of in-band crosstalk. Although the SOA gating in PONs has been proposed before [1], to the best of our knowledge, the high-speed gating performance of this scheme has never been experimentally tested. Here we describe for the first time a novel experimental technique for accurate characterisation of the dynamic extinction introduced by the SOA gating.

Experiments and discussion: Fig. 1*a* shows the structure of a new, low-cost, hybrid-integrated, tunable ONU transmitter that is currently under development within the PIEMAN project [1]. The ONU transmitter comprises a tunable laser diode, an electro-absorption modulator (EAM) and an SOA. While the EAM is employed for low-chirp, high-speed modulation at 10 Gbits, the SOA is required to compensate for the power loss due to the EAM and obtain a high output power (−5 dBm) [1]. Turning off the EAM does not solve the in-band crosstalk problem as this can only provide around 10 dB extinction. Instead, electro-optic switching of the SOA must be employed to provide sufficient suppression of the ONU's optical output power in the inactive state. Static characterisation of a commercially available discrete SOA (CIP SOA-S-OEC-1550) shows that >50 dB extinction, defined as the ratio between the power at the nominal bias current of 100 mA and the measured power, is achievable with the present technology (Fig. 1*b*). This level of extinction is in principle sufficient to allow a PON with more than 256 users to operate with negligible levels of in-band crosstalk [4].

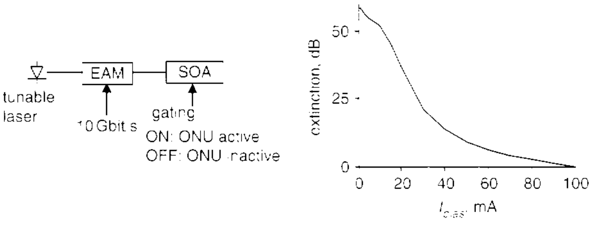

Fig. 1 *Structure of ONU and static characterisation of SOA extinction*
a Structure of ONU
b Static characterisation of SOA extinction

While the static off-state power of the SOA is sufficiently low to sustain a high number of users the dynamic behaviour could be affected by the transient response of the SOA. Although the 10–90% rise and fall times of these SOAs are less than 1 ns and thus much shorter than the inter-burst guard band (25 ns); even low levels of power due to long tails following the turn-off transient could still introduce significant levels of noise in following packets. A direct measurement of the SOA dynamic attenuation using, for example, a photodiode and an oscilloscope is not possible as the off-state power of the SOA is below the minimum sensitivity levels of the instrument. Hence we developed a novel way to characterise the dynamic extinction based on the bit error rate (BER) penalty induced by the interference from the SOA off-state emission.

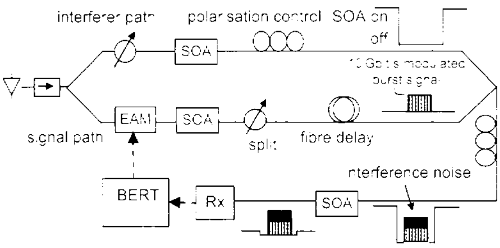

Fig. 2 *Experimental setup*

Fig. 2 shows a Mach-Zehnder system used for measuring the effect of interference from controlled amounts of SOA off-state emission where the ONUs are emulated using discrete components and a DFB instead of an integrated tunable laser. The SOAs used in the experiments are high gain (20 dB), low noise figure (7 dB) with >8 dBm saturated output. The devices are optimised for low bias current operation (~100 mA) to enable fast electrical switching with commercial semiconductor laser drivers. One path is regarded as the signal and the other the interferer. The attenuator denoted as 'split' in the Figure adjusts the power level of the signal arm to emulate the effect of the off-state emission from 511 inactive ONUs interfering with the signal generated by one active ONU. The 'fibre delay' line in the signal arm ensures that the optical path difference between the two arms exceeds the coherence length of the 50 MHz linewidth DFB laser. Polarisation controllers were adjusted to ensure that the two paths had identical polarisation, which would correspond to the highest level of interference noise and hence the worst-case situation in an actual network. Light in the signal arm was modulated using an EAM to 10 Gbit/s bit rate with burst packets each consisting of three blocks of $2^7 - 1$ (127 bits) pseudorandom bit sequence (PRBS)

(Fig. 3 inset). Burst signal and burst interferer packet envelopes were generated by gating the SOAs appropriately using a pulse generator. During the on-state the SOAs were biased at 100 mA to provide an average output power of −5 dBm and then switched to a suitable low bias current value to emulate optical power leakage when an ONU is in the off-state. To avoid receiver overload, a third gating SOA was placed before the receiver to suppress the high power on-state light from the interferer arm and allow only the signal packets to pass through. The high split ratio emulated leads to low input power levels at the third gating SOA reducing the optical signal to noise ratio to 25 dB, which introduces ~0.5 dB penalty at BER 10^{-9}. The penalty is, however, identical in all measurements and hence does not affect the estimation of the in-band crosstalk effect. The BER was measured selectively in the signal bursts at the receiver using the error-location capability of a 12.5 Gbit/s digital error analyser (BERTSCOPE 12500A).

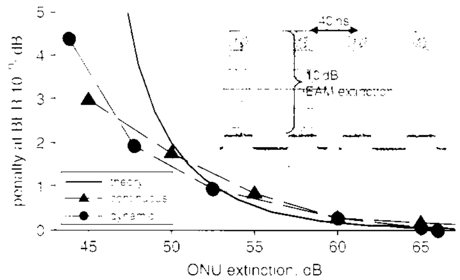

Fig. 3 *Optical power penalty against ONU extinction for 512 users and signal packet trace*

To deduce the performance degradation due to the dynamic behaviour of the SOAs, a comparison should be made with characterisation results obtained when the ONU operates in continuous mode. The same setup and experimental procedures were used in the case of continuous mode characterisation except that the SOAs were not gated and a 2^7-1 PRBS was used. The SOAs in both arms were operated at constant bias currents, with a fixed 100 mA current for the SOA in the signal arm corresponding to the ONU on-state and a suitable low bias current value for the SOA in the interferer arm.

The crosstalk penalty induced is plotted against the ONU extinction in Fig. 3 for continuous mode and dynamic characterisation. The different levels of extinction have been obtained by changing the off-state bias current of the SOA according to static characterisation of the device (Fig. 1*b*). Continuous mode characterisation of crosstalk penalty for different network applications has been experimentally investigated previously [5] and the results are in agreement with the current measurements. Fig. 3 also shows the penalty predicted by theory, calculated using a standard model of beat noise caused by multiple crosstalk [5]. There is good agreement with the experiments, considering that the theory assumes Gaussian statistics, which is a valid assumption for a large number of uncorrelated interferers, while in the experiments there is only one interferer, causing the slightly lower measured penalties [5]. It is, however, important to note that in a real network implementation the Gaussian assumption is valid owing to the large number of interferers.

The comparison of continuous mode and dynamic behaviour allows the quality of the SOA transient response to be evaluated. Any extra impairment induced by the dynamic gating of the SOA would be represented as an additional penalty compared to the continuous mode characterisation curve. The results show that this is not the case, since no extra penalty has been induced by the dynamic switching of the SOA. The maximum extinction obtained by gating the SOA used in the current ONU design is 67 dB. This extinction corresponds to a negligible (< 0.1 dB) power penalty indicating that this is sufficient to allow the operation of long-reach PONs with 512 users, if all interferers encounter the same loss as the signal [2].

Conclusions: A novel experimental technique to characterise the dynamic extinction of SOAs, used for ONU gating in next-generation PONs is presented. The technique is based on burst-mode measurement of the BER penalty induced by the interference from the SOA off state emission. The discrete SOAs used in the current ONU design can be effectively gated to provide a maximum ONU extinction of 67 dB. Under these operating conditions the experimental interference penalties due to in-band crosstalk are negligible, which suggests the feasibility of this ONU approach for long-reach PONs with up to 512 users.

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References

1 Talli, G., Chow, C.W., Townsend, P., Davey, R., De Ridder, T., Qiu, X.Z., Ossieur, P., Krimmel, H.G., Smith, D., Lealman, I., Poustie, A., Randel, S., and Rohde, H.: 'Integrated metro and access network: PIEMAN', Proc. NOC, July 2007, Sweden

2 Baekelandt, B., Mélange, C., Bauwelinck, J., Ossieur, P., De Ridder, T., Qiu, X.Z., and Vandewege, J.: 'OSNR penalty imposed by linear in-band crosstalk caused by interburst residual power in multipoint-to-point networks', *IEEE Photonics Technol. Lett.*, 2008, **20**, (8), pp. 587–589

3 Bauwelinck, J., Chen, W., Verhulst, D., Martens, Y., Ossieur, P., Qiu, X.Z., and Vandewege, J.: 'A high-resolution burst-mode transmitter with fast and accurate optical level monitoring for a 1.25-Gb/s upstream PON', *IEEE J. Solid-State Circuits*, 2005, **40**, (6), pp. 1322–1330

4 Yang, S., and Yao, J.G.: 'Impact of crosstalk induced beat noise on the size of semiconductor laser amplifier based optical space switch structures', *IEEE Photonics Technol. Lett.*, 1996, **8**, (7), pp. 894–896

5 Takahashi, H., Oda, K., and Toba, H.: 'Impact of crosstalk in an arrayed waveguide multiplexer on N × N optical interconnection', *J. Lightwave Technol.*, 1996, **14**, (6), pp. 1097–1105

Quantum dash actively modelocked Fabry-Perot laser module demonstrated as part of wavelength tunable RZ transmitter

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A quantum dash Fabry-Perot actively modelocked laser module is tested as part of a 42.7 Gbit/s transmitter with more than 10 nm wavelength tunability. Its low chirp level is also assessed through chromatic dispersion tolerance measurements.

Introduction: Modelocked laser diodes (MLLDs) have a great potential for many applications in optical communications, such as optical time-division multiplexing [1] or optical clock recovery [2, 3]. Furthermore, multi-wavelength lasers have become attractive as they enable one to obtain a large number of wavelength-division-multiplexing (WDM) channels from a single source [4, 5]. Future WDM light sources must meet a number of criteria such as simple and stable operation, cost effectiveness and low energy consumption. Quantum dash (QD) Fabry-Perot (FP) MLLDs are promising candidates as they meet all the above criteria. In addition these components have a small footprint, hold possibilities for monolithic integration and have recently shown the possibility to generate short pulses over a wide spectral bandwidth through passive filtering [6]. This last reference deals with spectral and temporal characterisations performed thanks to the linear spectrogram method [7].

In this Letter, a 42.7 Gbit/s RZ transmitter using the QD FP MLLD module is assessed thanks to bit error rate (BER) measurements, and its chirp is evaluated through chromatic dispersion tolerance investigations.

Contents

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