technique opens the possibility to the transmission of multiple analogue signals over DWDM systems supporting the chromatic dispersion penalty without using additional optical devices or special intensity modulators.

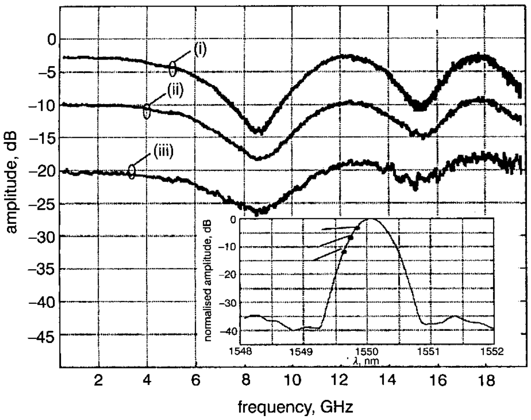

Fig. 4 *CSE amplitude (electrical-dB (i.e. 20 log (P_{out}/P_{in}))*
(i) to (iii) are optical carrier locations in inset

Acknowledgments: The authors wish to acknowledge the financial support to the projects from CICYT -TEL 99-0437 and IST-2001-32786 (NEFERTITI).

 25 April 2002
Electronics Letters Online No: 20020786
DOI: 10.1049/el:20020786

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Photonic integrated receiver for 40 Gbit/s transmission

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A novel 40 Gbit/s optical receiver is presented. The device consists of a waveguide photodiode integrated with a semiconductor optical amplifier. The receiver has a small signal bandwidth of 39 GHz and a conversion gain of more than 800 V/W. A back-to-back sensitivity of −17 dBm has been demonstrated for non-return to zero data transmission at 40 Gbit/s. A sensitivity of −32 dBm or 110 photons/bit has been realised for 40 Gbit/s return to zero transmission with an erbium doped fibre preamplifier and an optical filter.

Introduction: The sensitivity of conventional high-speed optical receivers consisting of *pin* photodetectors and electrical transimpedance amplifiers (TIA) is fundamentally limited by the front-end noise in the electrical amplifier. For higher bit rate systems the sensitivity of a direct detection receiver degrades due to increased noise bandwidth and higher input referred noise spectral density. To achieve better sensitivity, avalanche photodiodes (APD) are used in 2.5 and 10 Gbit/s receivers. However, at 40 Gbit/s line rates, it is difficult to achieve the gain bandwidth product required to make these devices practical. The best reported APD devices have shown a maximum gain of 3 dB at a bandwidth of 35 GHz [1] whereas *pin* detectors with integrated SOAs have been demonstrated with up to 20 dB of gain at this bandwidth [2].

For many long haul applications an erbium doped fibre preamplifier is used before the receiver with an optical filter to suppress the amplified spontaneous emission noise. Typically the EDFA gain can be high enough that the front-end noise in the electrical receiver becomes insignificant. Experiments have also been performed using semiconductor based optical amplifiers with external filters [3]. Despite the higher inherent noise figure of these devices when compared to EDFA preamplifiers, receiver sensitivities of −29.5 dBm at 8 Gbit/s have been demonstrated. In this Letter we discuss a new type of receiver, which integrates a semiconductor optical amplifier monolithically with a *pin* photodiode for high sensitivity 40 Gbit/s operation. This integration replaces the electrical transimpedance amplifier used in a conventional receiver with a semiconductor optical amplifier (SOA). Improved sensitivity, higher conversion gain, and greater dynamic range are achieved by using an SOA over an electrical post amplifier.

Device design: A cross section of the integrated amplified detector is shown in Fig. 1. The device incorporates a semiconductor optical amplifier, a waveguide *pin* photodetector, a butt joint regrown beam expander, and a passive waveguide isolation section. The detector has the same compressive strained multi-quantum well active layer as the SOA. This makes the device sensitive only to TE polarised light. The 100 μm long isolation section between the detector and the SOA and the 250 μm long beam expander are plasma hydrogenated to passivate the *p*-type material. This improves the electrical isolation between the SOA and *pin* sections, and reduces the optical loss from intervalence band absorption.

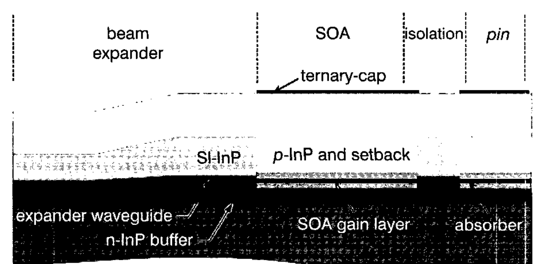

Fig. 1 *Cross section of PIR showing beam expander, semiconductor optical amplifier, isolation, and pin detector sections*

The device is fabricated using a deep ridge buried heterostructure technology (DRBH) [4] which buries the waveguide with an Fe doped InP blocking structure. The SOA length is 600 μm and the detector is 80 μm long. The die has top side *n* and *p* contacts enabling it to be flip chip mounted onto an aluminium nitride submount with an integrated broadband matching network, bias-T, and coplanar waveguide that connects the signal to a V-connector launch. This design eliminates ribbon bonds in the RF signal path significantly improving the performance and repeatability of the interconnections.

Experimental results: The small signal bandwidth of the receiver is 39 GHz measured using a 50 GHz network analyser and a calibrated modulator. The amplifier gain was measured over a range of bias currents from 20 to 65 mA at an input power level of −6 dBm, giving values between 4 and 14 dB. The measured input fibre coupling efficiency was 49%. The output coupling between the SOA and the detector could not be measured directly but was estimated to be greater than 95% from beam propagation method calculations.

The conversion gain and eye response for the photonic integrated receiver (PIR) was compared to a conventional 40G *pin*-TIA receiver with a conversion gain of 160 V/W. The eye diagrams for the conventional receiver and for the PIR at 64 mA SOA bias current are shown in Fig. 2 for a 40 Gbit/s non-return to zero (NRZ) pseudo-random bit sequence with a $2^{31}-1$ word length.

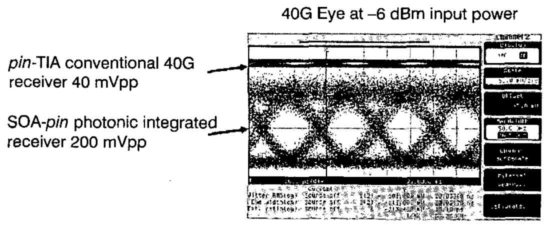

Fig. 2 *Eye diagrams for commercial 40G receiver with 160 V/W, and photonic integrated receiver with 800 V/W*

Comparison is shown at 40 Gbit/s and −6 dBm input power

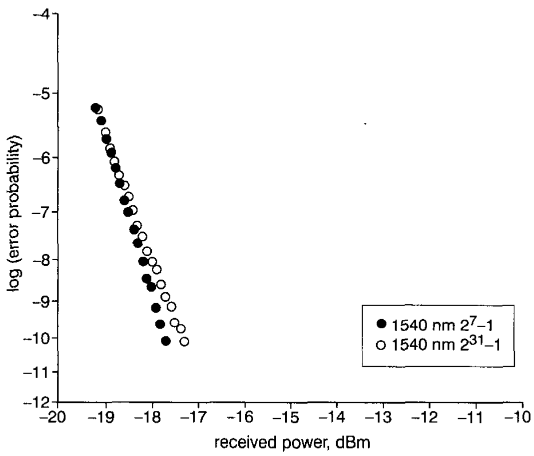

Fig. 3 *Bit error ratio curves for 40G NRZ data direct detection shows −17 dBm sensitivity at* 10^{-10}

The PIR was capable of generating a 200 mVpp output swing into a 50 Ω load with only −6 dBm input power giving it nearly 5 times the gain of the *pin* TIA. Output signal levels from 10 mVpp to 250 mVpp were achievable by varying the SOA current from 10 to 50 mA at −3 dBm input power. Broadening of the top rail is observable for signal levels in excess of 200 mVpp due to the signal spontaneous beat noise and pattern dependent saturation effects in the SOA. By approximating the ASE noise as Gaussian we can use the explicit expressions developed by Ruhl and Ayre [5] to predict the receiver sensitivity for these devices. We assume an input signal with a 12 dB extinction ratio. The SOA in the PIR has an 8 dB noise figure and a 60 nm optical bandwidth. For an SOA gain of 14 dB, and an estimated electrical noise spectral density of 13 $pA/Hz^{1/2}$ the 10^{-10} BER sensitivity for the PIR would be −20.7 dBm. For the conventional receiver the predicted sensitivity based on an input referred noise for the TIA of 20 $pA/Hz^{1/2}$ is −11 dBm.

The direct detection sensitivities for both receivers were measured using a 40 Gbit/s NRZ optical signal and a 40G demultiplexer with an input sensitivity of 50 mVpp. The conventional receiver had a 10^{-10} BER sensitivity of −8 dBm and the PIR had a sensitivity of −17.2 dBm at an SOA bias of 120 mA (Fig. 3). The discrepancy between the calculated and measured values can be attributed to the finite uncertainty in the decision threshold which was not included in this calculation [6]. The PIR was also tested in an optically preamplified configuration with an input EDFA and filter. For RZ transmission the sensitivity was −32 dBm or 110 photons per bit, which is approximately 1 dB better than the sensitivity for the conventional receiver (Fig. 4). This difference is most likely due to the flatter frequency response for the PIR. For NRZ transmission a receiver sensitivity of −30 dBm was measured with less than 0.5 dB of variation from 1540 to 1560 nm. The lack of an optical filter between the SOA and the detector introduces a calculated penalty of 2.8 dB for the direct detection configuration and the noise figure of the SOA limits the maximum predicted sensitivity for the PIR to about −22 dBm at higher amplifier gains.

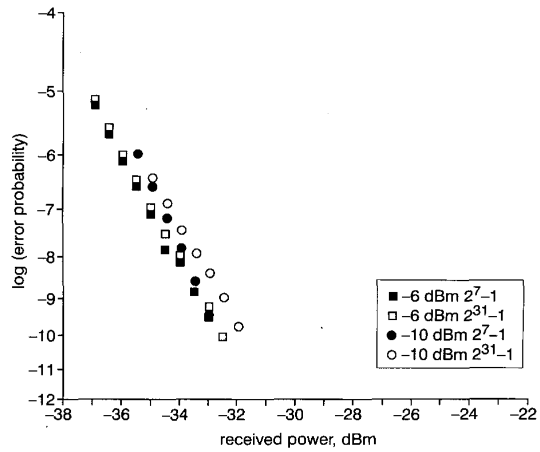

Fig. 4 *Bit error ratio curves for 40G RZ data with optical preamplifier shows −32 dBm sensitivity for 40G RZ data with −6 dBm into receiver*

Conclusion: We have demonstrated a photonic integrated receiver with 5 times the conversion gain of a conventional 40G receiver, 9 dB better sensitivity for direct detection, and 1 dB better sensitivity for optically preamplified detection. This improved performance makes it preferable for use in both long haul systems with EDFA preamplifiers and in short distance systems with high span loss.

9 July 2002

Electronics Letters Online No: 20020778

DOI: 10.1049/el:20020778

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