respectively, for the worst channel. Further optimisation of these parameters will yield even better results. Fig. 4 shows the eye diagrams after transmission for channels 4 and 8. Slight degradation was observed in the waveforms indicating penalties from chirps and nonlinearity effect.

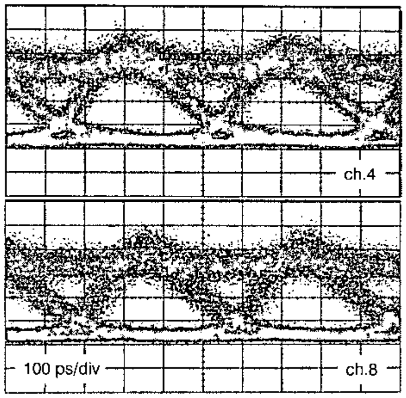

Fig. 4 *Eye diagrams for channels 4 and 8 after transmission*

We simulated signal power evolution along the 300 km span for eight channels using parameters measured from this experiment. The highest power that each channel can reach is ~+11 dBm, slightly above the onset of cross-phase modulation. To reduce XPM, we could drop the signal launch power or reduce the co-pumping Raman pump power; however, either approach will cause OSNR degradation. One potential solution is to use second-order Raman pumping, which can further improve OSNR and provide more distributed gain to reduce nonlinearity, but at a higher cost. This approach is currently under investigation.

Conclusions: We have successfully transmitted eight *C*-band channels (100 GHz spacing) error-free over 300 km of SSMF (63.5 dB loss) repeaterlessly using directly modulated lasers, APD receivers, and all-Raman amplification. The enabling technologies are Agere low chirp DMLs, high sensitivity APD receivers, and high performance Raman pumps. We have also demonstrated the cost effectiveness of this approach compared to similar transmission systems using conventional technologies by eliminating in-line EDFAs and LN modulated transmitters. Expanding more channels beyond eight is possible by adding additional Raman pump wavelengths. Our approach supports modularity and the 'pay as you grow' model.

1 October 2002
Electronics Letters Online No: 20030008
DOI: 10.1049/el:20030008

Leah L. Wang, T. Aherne and O. Mizuhara (*Agere Systems, 9999 Hamilton Blvd, Breinigsville, PA 18031, USA*)

E-mail: llwang1@agere.com

Jianjun Yu, V. Milner, K. Kojima and V. Swaminathan (*Agere System, 600 Mountain Avenue, Murray Hill, NJ 07974, USA*)

References

1 ROUX, P. LE., BOUBAL, F., BRANDON, E., BUET, L., DARBOIS, N., HAVARD, V., LABRUNIE, L., PIRIOU, L., TRAN, A., and BLONDEL, J.P.: '25 GHz spaced DWDM 160 × 10.66 Gb/s unrepeatered transmission over 380 km'. ECOC2001, Amsterdam, The Netherlands, Paper PD.1.2

2 BLONDEL, J.P., BRANDON, E., LABRUNIE, L., ROUX, P.L., and TOULLIER, D.: 'Error-free 32 × 10 Gb/s unrepeatered transmission over 450 km'. ECOC1999, Nice, France, Paper PD2-6

High sensitivity and wide-dynamic-range optical receiver for 40 Gbit/s optical communication networks

R. Vetury, I. Gontijo, Yet-zen Liu, K. Krishnamurthy, R. Pullela and M.J. Rodwell

An optical receiver for 40 Gbit/s communication networks demonstrating very high sensitivity without optical amplification has been developed. The receiver comprises an InP-based *pin* diode and HBT transimpedance amplifier. The receiver achieves a back-to-back sensitivity of −9 dBm and a high dynamic range of 13 dBm, measured using a pseudorandom binary sequence of $2^{31} - 1$ at a bit error rate of 10^{-12}. These results show the highest sensitivity and widest dynamic range yet reported for 40 Gbit/s optical receivers without optical amplification.

Introduction: Optical receivers at the front end of optoelectronic transceiver modules are a key component that influence the performance and cost of optical communication networks. The sensitivity of the receiver is one of the key parameters that decides repeater spacing and also imposes stringent performance requirements on optical amplifiers within the link. Although a number of wideband optical receivers suitable for data transmission rates of 40 Gbit/s using both return-to-zero (RZ) and non-return-to-zero (NRZ) formats have been reported [1–3], these receivers use optical amplifiers to amplify the optical signal before it undergoes an optical to electrical (O-to-E) conversion. In these reports, the optical signal power incident on the photodiode, which performs the O-to-E conversion, is maintained at a constant power level. The use of optical amplifiers adds to system size, cost and complexity. To the best of our knowledge, there has been no report of receiver sensitivity in a 40 Gbit/s data transmission link without the use of optical amplifiers. In this Letter, we report the development of an optical receiver that achieves a back-to-back sensitivity of −9 dBm at a bit error rate (BER) of 10^{-12}, as well as a wide dynamic range of 13 dB, measured using a pseudorandom binary sequence (PRBS) of pattern length $2^{31} - 1$.

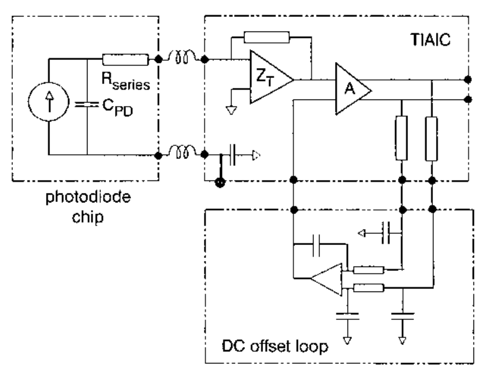

Fig. 1 *Schematic diagram of receiver*

Design of receiver: The receiver is composed of an InP-based waveguide *pin* photodiode (PD) that is directly coupled to a transimpedance amplifier (TIA) implemented in InP HBT technology, as shown in Fig. 1. The input impedance of the transimpedance amplifier is designed to optimise the wide band performance of the receiver taking into account the photodiode capacitance and resistance and the bond wire inductance. At 40 Gbit/s data rates, the parasitic bond wire inductances involved in coupling the PD output to the TIA as well as the ground inductance associated with bond wires connecting the TIA IC to the receiver package become critical and must be taken into account. The TIA is split into two stages, a linear transimpedance stage and an additional gain stage that also converts the signal from single ended to differential. The differential design is chosen for its high power supply rejection and the availability of a second output for monitor purposes, e.g. to measure the extinction ratio of the input photo-signal. Since a single ended to differential conversion occurs inside the TIA, a reference signal that is dependent on the magnitude of the input photo-signal is needed to balance the TIA outputs. A DC offset restoration loop that supplies this reference signal is implemented within the receiver. This loop is designed so that the low frequency components attenuated by the loop are a very small fraction of the total energy present in the input signal.

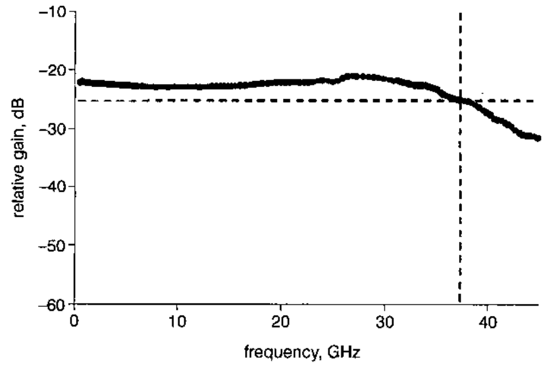

Fig. 2 *Measured frequency response of receiver, data obtained using an optical heterodyne measurement system*

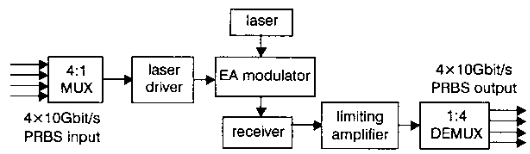

Fig. 3 *Schematic diagram of link for measuring BER*

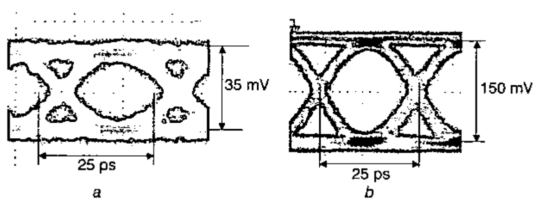

Fig. 4 *NRZ eye diagram at output of receiver*

a At input optical power of −9 dBm

b At input optical power of −2.5 dBm

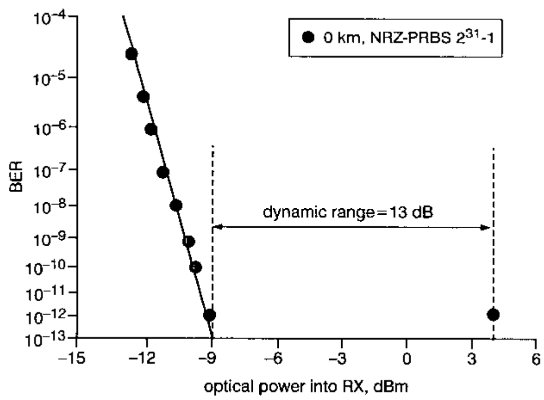

Fig. 5 *BER measurement result of link, showing sensitivity of −9 dBm and dynamic range of +4 dBm*

Measurements: Small signal measurements of the receiver using an optical heterodyne system are shown in Fig. 2. The responsivity of the photodiode is 0.7 A/W. The conversion gain of the receiver is 550 V/W (differential). The receiver has a small signal bandwidth of 35 GHz, limited primarily by the bandwidth of the PD. BER measurements were carried out using the measurement setup shown in Fig. 3. Four 10 Gbit/s PRBS were electrically multiplexed together to generate a 40 Gbit/s PRBS. This was input to a modulator driver driving an electroabsorption modulator. The received electrical signal from the receiver was demultiplexed (1:4) and data from a single channel was connected to the BER tester. The eye diagrams measured at the output of the receiver are shown in Figs. 4*a*–*b*. The plot of BER with respect to input optical power into the receiver is shown in Fig. 5. The data is shown for a pattern length of $2^{31}-1$ bits. No dependency on pattern length was observed, indicating that the gain and group delay performance at the low frequency cutoff of the receiver was adequate. A sensitivity of −9 dBm was obtained as well as an overload margin of +4.0 dBm.

Conclusions: An optical receiver for 40 Gbit/s communication networks with very high sensitivity without optical amplification has been developed. The receiver comprises an InP-based *pin* diode and HBT transimpedance amplifier. The receiver achieves a sensitivity of −9 dBm and a high dynamic range of 13 dBm. To our best knowledge, this is the best reported sensitivity and dynamic range for a receiver without optical amplification at 40 Gbit/s.

Acknowledgments: A. Rodriguez and R. Fernandez are acknowledged for expert work on wire bonding and assembly of the receivers.

23 October 2002

Electronics Letters Online No: 20030023

DOI: 10.1049/el:20030023

R. Vetury, K. Krishnamurthy, Yet-zen Liu and R. Pullela (*GTRAN Inc., 2651 Lavery Court, Newbury Park, CA 91320, USA*)

E-mail: vetury@yahoo.com

I. Gontijo (*OCP Inc, 20961 Knapp St, Chatsworth, CA 91311, USA*)

M.J. Rodwell (*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA*)

References

1 KUWAHARA, S., YONENAGA, K., MIYAMOTO, Y., MURATA, K., KITABAYASHI, H., HIMIZU, N., and TOBA, H.: '43 Gbit/s, 200 km unrepeatered transmission experiment using high sensitivity digital OEIC receiver module', *Electron. Lett.*, 2002, **38**, (1), pp. 38–40

2 OHIRA, R., AMAMIYA, Y., NIWA, T., NAGANO, N., TAKEUCHI, T., KURIOKA, C., CHUZENJI, T., and FUKUCHI, K.: 'A high sensitivity 40 Gbit/s optical receiver using packaged GaAs HBT-ICs'. Optical Fiber Conf., San Jose, CA, USA, 1998 Tech. Dig.

3 TAKAHATA, K., MIYAMOTO, Y., MURAMOTO, Y., FUKANO, H., and MATSUOKA, Y.: 'Ultrafast monolithic receiver OEIC module operating at over 40 Gbit/s', *Electron. Lett.*, 1999, **35**, (4), pp. 322–324

Long-haul 64 × 40 Gbit/s DWDM transmission over commercial fibre types with large operating margins

S. Banerjee, A. Agarwal, D.F. Grosz, A.P. Küng, D.N. Maywar, M. Movassaghi and T.H. Wood

Results are reported of 40 Gbit/s DWDM transmission over distances greater than 1000 km on several commercially available fibre types using a single 53 nm transmission band. The use of a wide singleband is made possible by forward and backward Raman amplification and makes for an easier system design and better footprint. Large *Q*-margins are demonstrated for all tested configurations.

Introduction: Projections of increased demand on capacity and reach for long-haul communication have resulted in many significant achievements in DWDM transmission systems at 10 and 40 Gbit/s data rate. Many of these technology demonstrations use innovations such as forward error correction (FEC), distributed Raman amplification, different modulation formats and/or specially engineered dispersion managed fibre [1–3]. Systems utilising the combined bandwidth in conventional C- and L-bands to increase capacity require band splitters and combiners, and separate optical amplifiers at each repeater site, adding significantly to cost and footprint. A different approach towards increasing reach and/or capacity is to use alter-