40 Gbit/s photonic receivers integrating UTC photodiodes with high- and low-confinement SOAs using quantum well intermixing and MOCVD regrowth

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Photonic receivers integrating unitravelling carrier (UTC) photodiodes with high saturation power/high gain semiconductor optical amplifiers (SOAs) are presented. The SOAs demonstrated up to 28 dB of gain with saturation output powers of up to 18.6 dBm, while the UTC photodiodes were capable of 40 Gbit/s operation under high photocurrent operation. The chip-coupled receiver sensitivity was better than −20 dBm at 40 Gbit/s. A high-flexibility quantum well intermixing and MOCVD regrowth integration method was used for device fabrication.

Introduction: Photonic integrated circuits (PICs) hold the potential to revolutionise the photonics industry. High-functionality PICs offering light generation, detection, modulation, amplification, switching, and transport on a single chip will facilitate reduced cost, size, and power dissipation. Optimised complex PICs will not only require multiple quantum well (QW) band edges, but will also need differing amounts of gain and optical confinement, and in some cases, a radically different internal structure. In a preamplified receiver consisting of an SOA and photodetector, a low optical confinement multiple QW (MQW) active region is attractive for high saturation power performance since the photon density within the QWs can be kept relatively low. The UTC photodiode is a unique photodetector structure developed specifically to mitigate the influence of hole transport on the operation of the detector facilitating superior photocurrent handling capabilities over conventional *pin*-type detectors.

With the addition of simple blanket regrowth steps to a robust quantum well intermixing (QWI) scheme, we have demonstrated a method to integrate UTC photodiodes and SOAs utilising gain regions of both low and high optical confinement with high performance widely-tunable transmitters [1, 2]. Here we report the results from photonic receivers comprising UTC photodiodes and SOAs fabricated on the same chip as 40 Gbit/s widely-tunable transmitters reported elsewhere [3]. The dual section SOAs contain a high optical confinement centred multiple quantum well (c-MQW) front-end for high incremental gain followed by a low optical confinement offset MQW (o-MQW) section for high saturation power. The SOAs demonstrated up to 28 dB of gain with saturation output powers of 18.2–18.6 dBm, and the photodiodes demonstrated 40 Gbit/s operation under high photocurrent operation. When combined to form photonic receivers, chip-coupled sensitivities better than −20 dBm were demonstrated at 40 Gbit/s. The fabrication method involved only simple blanket MOCVD regrowth steps.

Experiment: Device fabrication begins with MOCVD growth of the epitaxial base structure consisting of ten 6.5 nm QWs separated by 11 8.0 nm barriers centred within two InGaAsP:Si waveguide layers for maximum optical confinement in the MQW (12.6%). The samples were subjected to our QWI process described in [4] to shift the as-grown c-MQW peak photoluminescence (PL) wavelength from 1540 to 1505 nm in EAM regions, and to 1440 nm in regions where passive waveguides, low-confinement o-MQW sections, or UTC-type detectors were desired.

After completion of the QWI process, a blanket MOCVD regrowth was performed to deposit the low confinement o-MQW layer structure with a peak PL wavelength of 1550 nm. A 140 nm InP confinement tuning layer (CTL) was placed between the intermixed c-MQW and active o-MQW to yield an optical confinement factor of ~1.4% for the five offset wells. The sample was patterned and wet etched for selective removal of the o-MQW regrowth layer stack. A second blanket MOCVD regrowth was performed for the UTC photodiode layer structure. In this work we use a 200 nm InP collector layer and a 50 nm InGaAs:Zn absorber layer. Further details of the o-MQW and UTC layer structures can be found in [1, 2]. After selective removal of the UTC regrowth layer stack, a final blanket MOCVD regrowth was performed to grow the *p*-type InP:Zn cladding and *p*-contact InGaAs:Zn layers. A schematic side view illustrating the high confinement c-MQW regions, low confinement o-MQW regions, and UTC photodiode regions used in the photonic receivers is shown in Fig. 1.

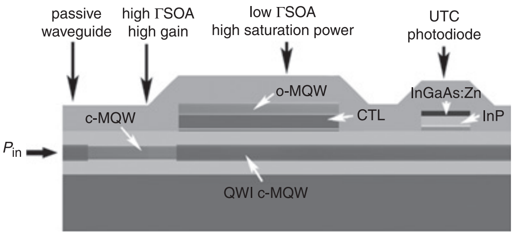

Fig. 1 *Side view schematic of device structure showing high confinement c-MQW gain region (left), low confinement o-MQW gain region (middle), UTC photodiode structure (right) grown over regions in which c-MQW has been intermixed*

Standard processing techniques were used for the definition of surface ridge waveguides and photo-benzocyclobutene was employed underneath the photodiode *p*-metal electrodes for capacitance reduction. The wafers were thinned, cleaved into bars, antireflection (AR) coated, separated into SOA/UTC receivers, soldered to AlN carriers, and wire bonded to a matched load of 50 Ω on the carrier for RF characterisation. The devices were placed on a copper stage cooled to 18°C for characterisation.

Results: The SOA/UTC receivers employed curved/flared input waveguides in addition to the AR coating to reduce facet reflections. The chip coupling loss was estimated to be ~4 dB. Two receiver designs were explored. The first design (design 1) consisted of a dual section SOA with a 5 × 250 μm high-gain c-MQW section and a 5 × 1650 μm high-saturation-power o-MQW section followed by a 3 × 30 μm UTC photodiode. The second design (design 2) consisted of a dual section SOA with a 5 × 400 μm high-gain c-MQW section and a 5 × 1500 μm high-saturation-power o-MQW section followed by a 3 × 40 μm UTC photodiode. The TE polarisation state was used during all testing owing to the polarisation sensitivity of the integrated SOAs.

The measured chip gain against input power characteristics is shown in Fig. 2 for the two SOA types at an input wavelength of 1550 nm. As shown in the Figure, design 1, making use of the 250 μm-long c-MQW section, provides a peak gain of over 22 dB and a saturation power of 18.6 dBm while design 2 with a 400 μm-long c-MQW section provides a peak gain of over 28 dB and a saturation output power of 18.2 dBm. The SOAs demonstrated less than 1 dB of gain deviation for input wavelengths from 1535 to 1565 nm.

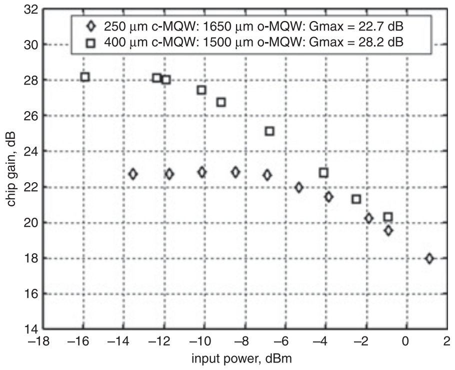

Fig. 2 *Gain against input power for dual section SOAs employing two different designs*

In both cases c-MQW sections operating at 15 kA/cm^2 and o-MQW sections operating at 6 kA/cm^2. Input wavelength 1550 nm

The internal quantum efficiency of the 30 and 40 μm-long photodiodes was measured at 28 and 32%, respectively, at an input wavelength of 1550 nm. The reduced UTC quantum efficiency from that demonstrated by previous devices reported in [1] is believed to be due to a fabrication issue. The frequency response of the UTC photodiodes was measured out to 20 GHz using an Agilent Lightwave Component Analyser (LCA). The detectors demonstrated only ~1 dB of roll-off at the 20 GHz limit of our testing capability with a 3 V reverse bias and an average photocurrent level of 20 mA.

To demonstrate high-speed receiver functionality, eye diagrams and bit error rate (BER) measurements were performed on the two receiver designs at 40 Gbit/s. A pseudorandom bit sequence of $2^7 - 1$ was used due to a noise floor in the bit error rate test setup at longer word lengths. The 40 Gbit/s non-return-to-zero signal was fed through a bandpass filter, optical attenuator and polarisation controller before entering the input waveguide where it was amplified in the SOA and detected in the UTC photodiode. The receiver output eye diagrams shown in Fig. 3 are clear and open. The device employing design 1 (Fig. 3*a*) demonstrates up to 300 mV of output amplitude, while the device employing design 2 (Fig. 3*b*) demonstrates up to 500 mV of output amplitude. As shown in the BER results of Fig. 4, receiver design 1 demonstrated error-free operation (10^{-9}) with a chip-coupled power of −16.8 dBm while receiver design 2 required only −20.2 dBm for error-free operation. The increased sensitivity of receiver design 2 is a result of the higher gain provided by the SOA and slightly higher quantum efficiency of the photodiode within this design.

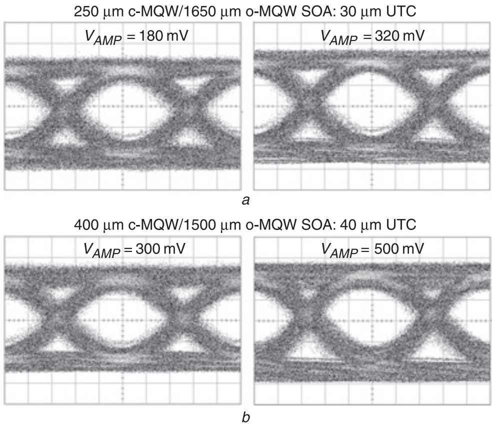

Fig. 3 *40 Gbit/s eye diagrams from receiver design 1 at c-MQW current density of 8 kA/cm^2 and receiver design 2 at c-MQW current density of 12 kA/cm^2*

a Design 1, c-MQW current density of 8 kA/cm^2
b Design 2, c-MQW current density of 12 kA/cm^2
In both cases o-MQW sections operated at 5 kA/cm^2 and detectors biased at 3 V

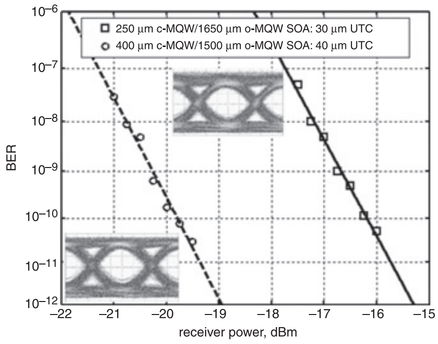

Fig. 4 *40 Gbit/s BER against received power for two dual section SOA/UTC photodiode receiver designs*

SOA operating conditions identical to those stated in Fig. 3
Insets: Eye diagrams

Conclusions: We have demonstrated 40 Gbit/s photonic receivers integrating low and high optical confinement SOAs with UTC photodiodes. The devices were fabricated on the same chip as widely-tunable 40 Gbit/s transmitters using a high-flexibility integration scheme. The SOAs within the receiver demonstrated up to 28 dB of gain with saturation output powers in the 18.5 dBm range and the UTC photodiodes were capable of 40 Gbit/s operation. BER measurements of the two receiver designs explored in this work demonstrated chip-coupled sensitivities of −16.8 and −20.2 dBm at 40 Gbit/s.

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