Single-chip, widely-tunable 10 Gbit/s photocurrent-driven wavelength converter incorporating a monolithically integrated laser transmitter and optical receiver

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A single-chip photocurrent-driven wavelength converter operating at 10 Gbit/s is presented. The device consists of a monolithically integrated widely tunable transmitter and an optical receiver. The transmitter consists of a sampled grating DBR laser, electroabsorption modulator and semiconductor optical amplifier (SOA). The optical receiver includes a quantum-well *pin* photodetector and a set of two SOA preamplifiers. Bit error rate measurements at 10 Gbit/s with a $2^{31}-1$ PRBS showed less than 1 dB of power penalty for conversion between 1550 nm and output wavelengths ranging from 1531 to 1563 nm.

Introduction: Dynamic wavelength switching in next generation optical networks will require improvements in traditional optical to electrical to optical (OEO) wavelength conversion techniques to achieve efficient wavelength routing [1]. From an integrated device perspective there have been several proposed solutions to this issue that utilise a variety of mechanisms. These include cross-gain, cross-phase and cross-absorption modulation along with an assortment of interferometric techniques [2, 3]. However, it has been challenging to demonstrate a device with a small form factor that does not require optical output signal filtering, operates at high bitrates, and is compatible with an on-chip laser source for efficient optical coupling between discrete components. For high bitrate applications where optical filtering is problematic, a particularly attractive solution is a single-chip photocurrent-driven-based device.

The electroabsorption modulator (EAM)-based photocurrent-driven approach relies on generation of a photocurrent from a detector that changes the voltage across an EAM, through a load resistor. This voltage modulates the transmission characteristics of the EAM, which is connected to a laser source operating at a different wavelength from the input. Using this technique, monolithically integrated photodetector and modulator devices without integrated lasers or amplifiers have been shown to be compatible with up to 500 Gbit/s [4]. Fully integrated wavelength converters have been demonstrated with tunable laser sources and amplifiers, but performance was limited to 2.5 Gbit/s as a result of low-efficiency Franz-Keldysh bulk waveguide EAMs and/or limited saturation output power in integrated optical amplifiers [5, 6]. In this Letter, the first 10 Gbit/s single-chip photocurrent-driven wavelength converter is demonstrated with bit error rate (BER) power penalties of less than 1 dB over a wide range of output wavelengths (32 nm). The fibre-coupled waveguide input power was −11 dBm, which, to the best of our knowledge, is the lowest reported for an integrated photocurrent-driven device.

Experiment: The wavelength converter consists of receiver and transmitter regions that are fabricated on neighbouring, parallel waveguides, as shown in Fig. 1. This configuration allows for complete separation of the optical input and output signals, eliminating the possibility of crosstalk and hence the need for optical filtering at the device output that is required by many other types of wavelength converters with on-chip sources. The receiver and transmitter waveguides are connected with a short (35 µm) Ti/Pt/Au metal interconnect to allow the generated photocurrent to be routed between the two sections. The receiver contains a set of two optical amplifiers that are operated in their linear regime, followed by a QW-*pin* photodetector. The first amplifier is 600 µm long and has a waveguide width of 3 µm. This SOA is used to boost the fibre-coupled input power level to just below the 1 dB gain compression point for a given operating current density. The second amplifier is 400 µm long and has an exponentially flared waveguide width (3–12 µm) to expand the cross-section of the optical mode. This geometry enhances the 1 dB output power compression of the SOA, while still allowing for gain at the expense of additional applied current [7]. The QW-*pin* photodetector is 50 µm long and is simply a reverse-biased region containing the offset quantum well (OQW) stack that is used for gain in the laser and amplifiers. The photodetector ridge width is linearly tapered down from 12 to 3 µm for low capacitance and increased saturation power. The transmitter section consists of a five-section widely tunable sampled grating distributed Bragg reflector (SGDBR) laser [8], a 550 µm optical amplifier and a 400 µm-long QW EAM. The EAM and the QW-*pin* photodetector share a common electrical reverse bias that is applied through a 50 µm pitch ground-signal probe in combination with an external bias tee that includes the 50 Ω load resistor. Low-*k* dielectric, photo-bis-benzocyclobutene (BCB), is incorporated in the QW-*pin*, EAM and the metal interconnect to minimise any parasitic capacitance from bondpads and metal electrodes.

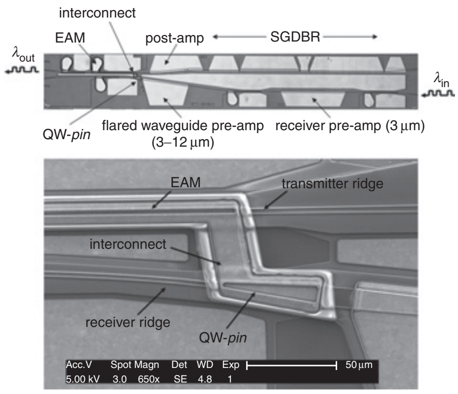
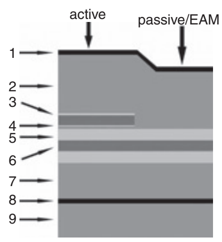


Fig. 1 *Scanning electron micrograph (SEM) images*

SEM images of monolithically integrated, small form factor (3.0 × 0.5 mm) wavelength converter (top)
SEM image of EAM/QW-*pin* interconnect (bottom)

The wavelength converter is fabricated in the InGaAsP/InP material system using exposed ridge waveguides on a dual quantum well (DQW) integration platform. This integration platform is very similar to the more common OQW platform that has previously been used for SGDBR-based photonic integrated circuits (PICs) [7]. Compared to the OQW approach, the DQW platform includes an additional set of quantum wells that are inserted into the optical waveguide region to enhance the modulation efficiency of the integrated EAMs. These waveguide quantum wells have a photoluminescence peak of 1480 nm and consist of 7 × 9.0 nm wells and 6 × 5.0 nm barriers. This platform is attractive since it uses all the processing techniques developed for the OQW PICs and requires only a single blanket *p*-InP overgrowth to fill in the gratings on the tunable laser. A diagram of the DQW integration platform with a detail of the individual layers is shown in Fig. 2.



region	description
1	*p*-contact
2	*p*-cladding
3	offset QWs
4	stop etch
5	waveguide
6	centred QWs
7	*n*-buffer
8	*n*-contact
9	Fe-substrate

Fig. 2 *Layer structure of DQW InGaAsP/InP integration platform*

Offset quantum wells are used for optical gain in amplifiers and gain section of laser. Waveguide quantum wells provide modulation efficiency for integrated EAMs

Results: Devices were antireflection (AR) coated and mounted on copper blocks for testing. The temperature in all the following experiments was maintained at 15°C. Optical to optical S_{21} response measurements of a 50 Ω terminated wavelength converter showed a 3 dB frequency roll-off of 7 GHz. Bias conditions in the frequency response measurement were −2.5 V over both EAM and QW-*pin* and the wavelength converter was operated with an input of 1548 nm and an output of 1565 nm. Characterisation of the discrete 400 µm EAM DC extinction for wavelengths between 1531 and 1563 nm showed greater than 20 dB total extinction with less than −4 V bias and slope efficiencies greater than 10 dB/V. The optical receiver, including both SOA preamplifiers and the QW-*pin* photodetector, was characterised and showed a collective output power 1 dB compression of +15 dBm along with 20 dB of gain at an applied current density of 6 kA/cm^2. The photodetector reverse bias was −2.5 V.

For the BER measurements, a non-return-to-zero (NRZ) $2^{31}-1$ pseudorandom bit stream at 10 Gbit/s from a BER tester transmitter (Agilent 83433A) was input into an EDFA followed by an optical filter and polarisation controller, then transmitted to the device using a lensed fibre. The wavelength converted signal was routed to a variable attenuator, followed by a photodetector and finally back to the bit-error-rate tester. The input optical fibre power level was −5.5 dBm, corresponding to −11 dBm of coupled waveguide power, and the input extinction ratio was 14 dB. The SGDBR gain and transmitter post-amplifier are biased at 130 and 120 mA, respectively, and the receiver preamplifiers are biased for a current density of 6 kA/cm^2.

Error-free operation (BER of 10^{-9}) is demonstrated (Fig. 3) with less than 1 dB power penalty for wavelength conversion between a fixed input wavelength of 1548 nm and a range of output wavelengths from 1531 to 1563 nm. The converted output extinction ratio varied between 8.7 and 9.2 dB and the average output powers, with fibre coupling losses removed, ranged between −1.8 and +2 dBm.

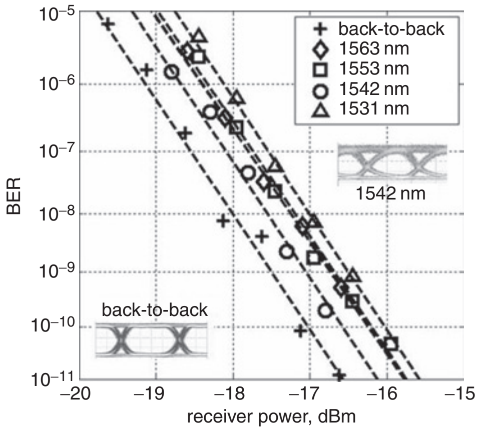


Fig. 3 *BER measurements at 10 Gbit/s for wavelength conversion between fixed input (1548 nm) to variable output (1531–1563 nm)*

Applied wavelength converter bias levels were −1.4, −2.0, −2.9 and −3.1 V for wavelengths of 1531, 1542, 1553 and 1563 nm, respectively. Optical eyes shown for back-to-back and wavelength converted (1542 nm) signals

Conclusions: We have demonstrated the first photocurrent-driven wavelength converter with a monolithically integrated tunable laser and optical receiver operating at 10 Gbit/s with BER power penalties of 1 dB over a wide output tuning range (32 nm). Input powers were kept at −5.5 dBm in the fibre and −11 dBm in the waveguide, which is to the best of our knowledge the lowest reported for this type of device.

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