Scalable Quantum Dot Optical Switch Matrix in the 1.55μm Wavelength Range

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Abstract: The first quantum dot based crossbar switch matrix is proposed, fabricated and demonstrated at a wavelength of 1.55μm. Power penalty measurements at 10Gb/s show minimal path dependence with values of 0.4 to 0.6 dB.

Keywords: Integrated optoelectronics, optical switches, quantum dots.

Introduction
Photonic integration is set to play an increasingly important role as a route to overcome packaging complexity and to enable power efficiency in next-generation interconnection technology. The integration of multiple switch elements to build up multiport switch matrices is readily achieved through the use of semiconductor optical amplifiers (SOAs) gates. SOAs offer a highly compact, potentially lossless and low crosstalk means of low-latency broadband switching. Four-input four-output (4 x 4) SOA-based integrated switches have been demonstrated using broadcast-select [1, 2] and crosspoint architectures [3, 4]. However both approaches are complex to scale beyond 4 x 4 due to the high numbers of waveguide crossings and required control signals. In work to date, epitaxial designs have also resulted in non-optimum saturation properties and therefore compromised performance at high data rate. Considerable research attention has recently been focussed on quantum dot (QD) amplifiers due to their ultra-broadband amplification, low distortion, high saturation output power and low noise figure [5]. Good cascaded performance further indicates the promise of suitability in multistage scalable switching fabrics [6]. A two input, two output quantum dot space switch has also been realised in the 1300nm wavelength range. In this work we scale interconnection to four inputs and four outputs in the first monolithic multistage SOA based switch. A quantum dot epitaxy at 1550nm is implemented for the first time in the demonstration of low power penalty routing at 10Gb/s.

2. Architecture
The switch matrix design is based on a novel photonic crossbar element with an integral waveguide crossing. One such crossbar matrix element is shown in Figure 1a. This element is implemented with common electrodes to reduce the required numbers of electrical connections. A further reduction in the number of control signals is also possible as complementary signals may be used for each 2x2 electrical element. Figure 1a shows the bar state addressed by biasing only pad 04 and cross state by biasing only pad 03. At the centre of the switch matrix, a reduced shuffle network is implemented to interconnect four crossbar switch elements (Figure 1b). The central shuffle network allows any optical input to be directed to any optical output by means of electronic addressing, although not necessarily simultaneously. This blocking behaviour might be addressed with an efficient packet time-scale media access protocol. The paths are implemented with a combination of multimode interference splitters (MMI) and combiners located within the input, shuffle and output regions (pads 00, 07 and 13 in figure 1). These are interconnected by two stages of cascaded SOA gates (pads 03-06 and 09-12) which are electronically configured. To fully operate the switch matrix, only four pads need to be in the on-state at any given time.

3. Circuit
The switch matrix is fabricated from a five stack quantum dot active layer [8], embedded in a Q1.15μm InGaAsP separate confinement heterostructure. Four parallel input and output waveguides on a 250μm pitch are shown on the left and right hand side of Figure 1b. The circuit is realised in a highly compact area of 3mm² with an all-active single step epitaxy. The circuit is die and wire bonded to a patterned ceramic tile. A multi-pin probe is used in combination with a reconfigurable electronic multiplexer to connect the current sources. The circuit is assessed on a temperature controlled stage at 15°C. Lens ended fibres are used for measurements. The mean fibre coupling loss between fibre and the chip is estimated from photocurrent measurements to be 8dB per facet, including an estimated 1.5dB loss through the cleaved facet. Direct power measurements give a typical 40dB off-state fibre-coupled loss. An electrical fail...
is observed at pad 05. DC currents are applied to combinations of five electrodes to form the switch paths. The input, output and shuffle pins are each operated at 200mA. The crossbar electrodes are selected according to the required state and are biased at 100mA. When one crossbar element is switched from "on" to "off" state, a change in gain of over 10dB is typically observed. Improved confinement layer design and longer gate length in the crossbar elements is expected to directly enhance gain and therefore crosstalk performance. Optical saturation properties have also been studied, with the dependence of the gain on input fibre coupled power being negligible up to +11dBm.

4. Routing at 10 Gb/s

The integrity of routed data is assessed with bit error rate (BER) measurements. These measurements were performed at a data rate of 10Gb/s with a pattern length of $2^{31}$-1 using the experimental arrangement outlined in figure 2. A fibre-coupled input power to the switch matrix of +11dBm is used at a wavelength of 1550nm. The switch matrix is polarisation sensitive and the injected state is optimised for minimum path loss. The bias state conditions are the same as for the static performance assessment. The output signal from the QD switch matrix is passed through a 0.7nm optical bandpass filter. This signal is pre-amplified by an Erbium fibre amplifier and input to a 10 Gb/s receiver and error detector. Power penalty measurements are obtained through BER measurements with and without the inclusion of the switch matrix.

Figure 2 : Set-up schematic for the chip assessment.

Error rates are shown in figure 3 as a function of received power for representative paths. The number of waveguide crossings and multimode interference (MMI) couplers and splitters are path dependent as reflected in the inset caption. Measured data show no indication of an error floor or distortion within the switch matrix itself. Power penalty varies only slightly with values between 0.4 to 0.6 dB for the range of paths indicating a weak power penalty dependence on selected path.

5. Conclusion

The first 1.55μm quantum dot semiconductor optical amplifier based crossbar switch matrix design is proposed, fabricated and demonstrated. The monolithic circuit exploits low distortion properties of the epitaxy to enable a compact, four input, four output switch matrix. The simplicity of the electrical connection is expected to enable a highly scalable SOA based photonic matrix switch architecture for higher connectivity switch matrices.

Figure 3 : Bit error rates of each selected path (l to O, Crossings, MMI). A trend-line for back to back data is given to assist the eye.

6. References