4 × 4 optical cross-point packet switch matrix with minimized path-dependent optical gain

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Packet-switching characteristics are optimized across an integrated 4 × 4 optical cross-point switch matrix based on active vertical coupler switch cells. Optical gain is demonstrated across the entire matrix with a <3-dB difference between the shortest and longest switching paths. © 2003 Optical Society of America

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High-speed optical switching fabrics able to route optical packets with low insertion loss, low added noise, and low cross talk are highly desirable for future optical packet switching networks.[1] Previously, Varazza *et al.*[2] and Yu *et al.*[3] proposed an optical cross-point switch (OXS) structure (Fig. 1a) integrated on InP substrates, consisting of interconnected optical switch cells based on active vertical couplers (AVCs) (Fig. 1b). Each switch cell connects two passive waveguides that intersect each other perpendicularly as input and output signal buses. At the cross point two AVCs are formed by a light-amplifying active waveguide layer grown on top of the passive waveguides. This allows switching via both carrier induced refractive index and gain–absorption changes. In the ON state carriers are injected into the switch cell. The refractive index of the active upper waveguide is reduced to match that of the lower waveguide to allow coupling. The input light signal is coupled up into the active layer in the first AVC, amplified and reflected by a total internal reflection (TIR) mirror cutting diagonally across the waveguide cross point and vertically through the active waveguide, and then coupled down to the output passive waveguide in the second AVC. In the OFF state the light signal passes through the cell along the input passive waveguide to the next switching cell (Fig. 1b).

Switch cells with very low cross talk , a high ON–OFF extinction ratio, and wide optical bandwidth performance were achieved in our past work.[2] It has also been demonstrated that the device has a very fast switching speed of ~1.5 ns, making it suitable for packet switching.[4] In addition, simultaneous packet switching and wavelength conversion with such a switch cell has also been demonstrated.[5]

However, the switch cells reported before showed poor on-chip transmission of ~−10 dB and had transmission loss in the OFF state in excess of 2 dB/cell. They were therefore insufficient for forming OXS matrices because the matrix would have undesirable high path-dependent loss and poor scalability. In this Letter we report on an optimized OXS structure for achieving uniform optical transmission via all switching paths on a 4 × 4 OXS matrix that minimizes path-dependent gain and transmission performance penalty across the matrix.

The approach to achieving good performance across the matrix is to first increase the individual switch cells' ON-state optical gain. This can generally be achieved by maximizing the carrier-induced effective refractive-index change in the active waveguide at the desired ON-state injection-current density level. The passive waveguide parameters are then adjusted so that good coupling is achieved at the ON-state current level. In an AVC structure the coupling length at which the optical power maximum occurs in the active layer differs from that of a classic passive directional structure and does not coincide with the length at which the optical power minimum occurs in the passive waveguide.

Apart from common reasons such as material, waveguide, and TIR mirror scattering losses, the OFF-state transmission loss is caused mainly by residual coupling of light into the active layer, which is now in a high absorption state. To achieve transmission uniformity, one should minimize the OFF-state loss of the switch cells. This is achievable by epilayer structure adjustments, resulting in longer coupler lengths. However, the physical size and the total injection-current–power-consumption requirements limit the coupler length. A trade-off between the AVC length and the OFF-state loss is thus necessary. Resulting designs do not necessarily provide maximum gain for each individual switch cell but will result in a 4 × 4 matrix with minimized path-dependent gain.

Several designs with two different cell sizes (250 μm^2 × 250 μm^2 and 500 μm^2 × 500 μm^2) have been generated. One of the structures, aiming at an OFF-state loss of ~0.5 dB/cell, has an intrinsic separated confinement heterostructure upper active

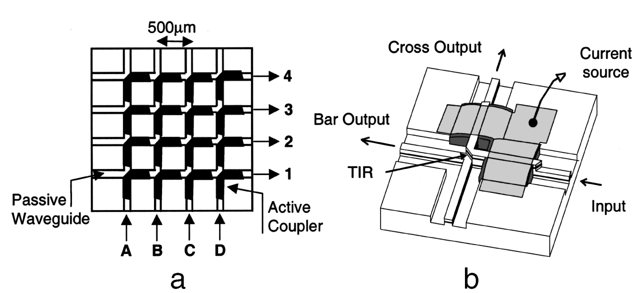

Fig. 1. a, 4 × 4 OXS matrix. b, Single optical switch cell.

waveguide with 0.7 nm × 7.5 nm unstrained InGaAs quantum wells (λ_{PL} = 1560 nm) and 6.0-nm Q1.3 barriers. The 0.7-μm-thick Q1.2 passive waveguide layer and the 1.35-μm-thick InP spacing layer are n doped. The wafers are grown by metal organic vapor phase epitaxy.

The switch matrices, with 5-μm ridge waveguide width and 500-μm cell size, are defined by a self-aligned two-level metal–dielectric masking scheme, allowing good alignment of the TIR mirror relative to the waveguides. The structure is etched in two dry etching steps by use of inductively coupled plasma/reactive ion etching in Cl_2/N_2 ambient, yielding high smoothness and verticality of the sidewall and the TIR mirror. SiO_2 passivation and Ti/Pd/Au p-contact deposition finishes the device. The 4 × 4 OXS matrix device used in this experiment is bonded to a copper heat sink with the device side up. The temperature of the heat sink is controlled at 20 °C by a thermoelectric cooler.

As shown in Fig. 2 a Hewlett–Packard HP8168E tunable laser source is used to generate an input signal in the wavelength range 1470–1580 nm, which is modulated into a series of light pulses synchronized with the switch current pulse generator. Then the pulsed light signal is coupled in and out of the 4 × 4 matrix by two fiber lenses. A polarization controller is also used to produce a TE-polarized input signal. At the output, the signal is filtered by a 3-nm optical bandpass filter.

Extensive lasing was observed on the as-cleaved chips. After antireflective treatment of the unused back facets, it has been observed that each switch cell has a lasing threshold that is cavity path-length (input–switch cell–output) dependent, forming a regular distribution across the device (see the inset of Fig. 3). The lowest threshold performances were observed with the shortest path of cell D1 (Fig. 1), increasing gradually with increasing path length. After front-facet antireflective treatment, the lasing threshold increased to values higher than 550 mA, confirming that lasing was due to Fabry–Perot resonance between the input and output facets. Figure 3 shows typical light–current curves before and after front-facet antireflection.

Switching characteristics across the 4 × 4 device were measured. Examples of the shortest, longest, and other paths across the 4 × 4 OXS matrix are plotted in Fig. 4, at the gain peak wavelength of the active waveguide and with TE polarization. All data are plotted after a total loss of ~18 dB is deducted from the measurement system, including the polarization controller, input–output coupling, and optical filter.

It was observed that all paths achieved lossless switching or optical gain. A difference of less than 3 dB was observed across the matrix (between longest and shortest paths) at a switch current of 550 mA when the device was in ON-state transmission. This result meets the design aim of 0.5 dB/cell OFF-state loss, because there are six OFF-state cells for the longest path. For most cells, currents higher than 550 mA result in excessive Fabry–Perot resonance that is due to imperfect facet antireflection. However, in some units higher gain was shown to be possible when the current was increased further. With the device in the OFF state (zero current), the measured on-chip leakage level between all inputs and outputs was as low as −67 dB, resulting in an ON–OFF contrast of ~70 dB at 500 mA. Furthermore, no increase in leakage signal levels could be measured in any other outputs with any switch path in the ON state, confirming the excellent cross-talk suppression in the switch matrix.

Each of the 16 switch cells of a 4 × 4 matrix was tested, and the average on-chip transmission with the standard deviance was calculated. As shown in Fig. 5, the average ON–OFF contrast of 70 dB was confirmed. The standard deviance can be as

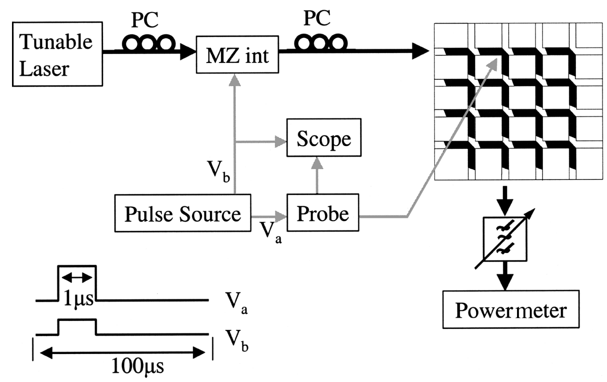

Fig. 2. Experimental setup. MZ int, Mach–Zehnder interferometer.

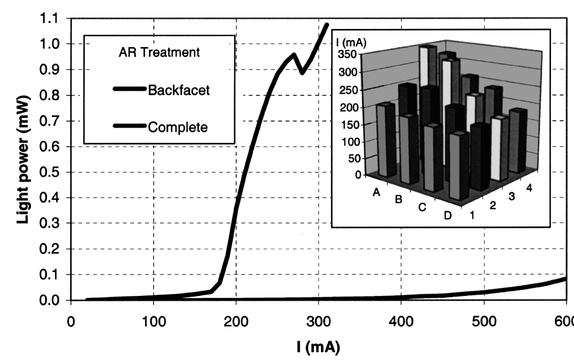

Fig. 3. Typical light–intensity curve and Ith distribution across the 4 × 4 optical switch cell matrix.

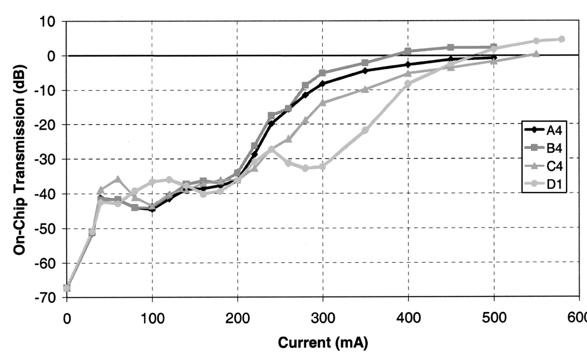

Fig. 4. Switching characteristics of the shortest (D1), the longest (A4), and the other two (C4, B4) paths across the 4 × 4 OXS matrix.

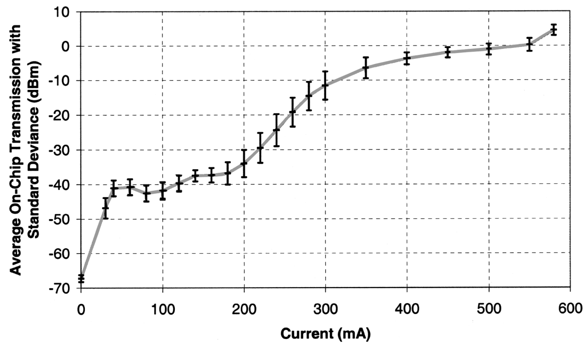

Fig. 5. 4×4 OXS matrix average switching characteristic and standard deviation.

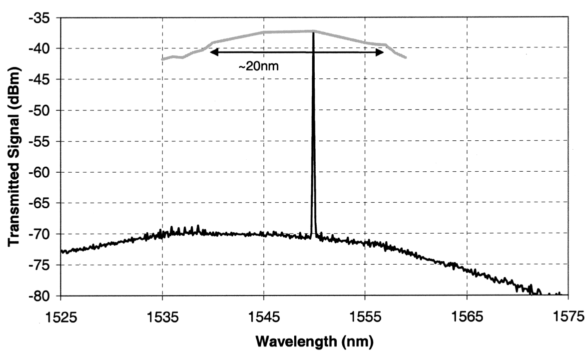

Fig. 6. Spectra of the 1550-nm switched signal and the 3-dB bandwidth.

large as 9 dB at the rising slope of the transmission curves, but it decreases to approximately 3–4 dB at the expected switching current value of 450 mA and above. This is still larger than the expected value of <3 dB, which is the difference between the longest and shortest switching paths. This larger-than-expected value may be attributed to wafer quality and fabrication quality inhomogeneities. For example, random defects in TIR mirrors and waveguide sidewalls can cause unexpected high loss in a small number of switching cells. At 0-dB input signal level, the unfiltered output spectrum is characterized by a switched signal peak of 34 dB above the device's spontaneous-emission floor. A gain-wavelength response measurement (envelope curve in Fig. 6) yields a 3-dB optical bandwidth of 20 nm in the C band.

A compact, integrated lossless 4×4 matrix optical switch has been optimized and fabricated on an InGaAsP/InP substrate. The switch employs optical switching cells based on active vertical coupler technology. The results have shown that the device has minimized path-dependent transmission between the longest and the shortest paths. Lossless switching with optical gain of up to 5 dB has been achieved across the matrix. Furthermore, an ON–OFF contrast as high as 70 dB and extremely low cross-talk levels of <-65 dB make the device highly promising. Future work will concentrate on improving the homogeneity of switching characteristics and on producing devices with minimized polarization-dependent loss.

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