Photonic crystal planar waveguide devices exploiting the thermo-optic effect

Richard De La Rue[1], Harold Chong, Edilson Camargo [a], Caterina Ciminelli [b] and Mario Armenise [b]
Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland, U.K., e-mail: r.delarue@elec.gla.ac.uk
[1]currently at IOTA, LCFIO-MANOLIA, Orsay, France
[a] Centro Técnico Aeroespacial, Praça Marechal Eduardo Gomes, 50, São José dos Campos, 12228-901, São Paulo,Brazil
[b]Laboratorio di Optoelettronica, Dipartimento di Elettrotecnica ed Elettronica, Politecnico di Bari, Via Re David 200, 70125, Bari (Italy), email: armenise@poliba.it

Summary

Photonic crystal devices are now being produced for a variety of functions – and the need to provide thermal control of the behaviour suggests the use of thermo-optic effects. It has emerged that thermo-optic effects can provide useful modulation, switching and tuning capability. Future trends indicate fast, low-power, thermo-optically operated photonic crystal and photonic wire devices – and the possibility of simultaneous athermal characteristics.

1. Introduction

Photonic-crystal (PhC) and Photonic-wire (PhW) structures fabricated in the high refractive index semiconductors provide a substantial part of the device technology for *nanophotonics*. The question might possibly be posed as to why semiconductors are relevant for nanophotonics? A simple response to this question is to note that, for example, both photonic and electronic device structures are routinely being produced in large volumes, using the *heteroepitaxial III-V semiconductor* aluminium-gallium-arsenide (GaAs/AlGaAs) system or similar material systems as a base. These devices may have structural features with well-submicron features, while being produced on gallium arsenide substrates with sizes typically as large as six inches (15 cm). Likewise silicon, and in particular *silicon-on-insulator* (SOI), is routinely available as wafers with typical diameters as large as eight inches (20 cm). Both silicon and *gallium arsenide* based material systems characteristically have high refractive indices. For telecom and high-frequency/large bandwidth electronics, hetero-epitaxial systems based on *indium phosphide* (InP) are also vitally important - and again this is a characteristically high refractive index semiconductor system. Like silicon, elementary germanium has a high refractive indices. The importance of germanium is currently increasing because the silicon-germanium material system can bring major improvments in electron-device performance – and because quantum-cascade (QC) unipolar devices based on the Si-Ge system could provide light sources for the mid- to far-infrared. All of the example materials that we have now cited exhibit electronic band-gaps/absorption-edges in the near infra-red, implying the possibilities of useful transparency at longer wavelengths - and photo-detection capability at shorter wavelengths. The direct-bandgap III-V semiconductors also characteristically provide current-injection electroluminescence at un-surpassed electrical-optical (electron-photon) conversion efficiency.

Photonic Materials, Devices, and Applications, edited by
Gonçal Badenes, Derek Abbott, Ali Serpengüzel, Proc. of SPIE Vol. 5840
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.608680

The high refractive indices that are typical of inorganic semiconductors are one of the key aspects that have motivated the field of photonic crystals and the quest for obtaining photonic band-gap (PBG) behaviour. Relatively large thermo-optic effects naturally accompany high material refractive index values - and simultaneously imply significant susceptibility of device properties such as microcavity resonance frequencies to changes in operating temperature. This paper is primarily concerned with planar photonic crystal devices and the possibilities for obtaining useful device functionality by exploiting electronically initiated thermo-optic effects in the photonic crystal domain. It is also concerned with the question of controlling device performance when the operating ambient temperature changes. These issues are important for the wider domain of nanophotonics that includes photonic wire devices. In the present context, the significance of the availability of large-area wafer sections, while considering the domain of nanophotonics, is also related to the mass-production aspects of semiconductor technology - with VLSI chip microelectronics pushing device feature sizes ('nodes') well below 100 nm.

2. Active control of photonic crystal and photonic wire device structures

For active control of photonic devices, various effects are available – including current injection and several forms of electro-optic effect. But in silicon, the most obvious of these effects, the linear electro-optic (Pockels) effect is not available because of its centro-symmetric atomic crystal structure. Current injection, most obviously via some form of transistor structure, is available – but intrinsically leads to a combination of both *amplitude* and *phase* modulation, since the real and imaginary parts of the refractive index are modified simultaneously by changes in free-carrier density. Carrier injection is also accompanied by ohmic heating and dissipation. In both typrd of high refractive index semiconductor (group IV and III-V), there is a large, positive temperature coefficient for the refractive index. This property poses the question of whether the properties of photonic crystal or photonic wire devices where, for instance, very high resonance Q-factors have been demonstrated will be excessively vulnerable to the effects of changes in temperature. One possible reason for considering the application of thermo-optic effects is simply that, with both heating and refrigeration possibilities available, they may be useful in compensating for the effects of ambient temperature variation. But the same thermo-optic temperature tunability can possibly be exploited directly to select and change the frequency at which a micro-cavity resonance occurs. Various time-varying functional inputs, such as cyclic ramping or sinusoidal scanning become possibly, provided that the thermal response time is appropriate for the scanning rate required by a particular application.

We have applied the thermo-optic effect in several different devices. In one experiment, a planar PhC channel waveguide microcavity using SOI material was tuned thermooptically. A patterned resistive metal film deposited on top of the microcavity was used as the heater, with a thin (~200 nm thick) silica buffer layer providing both electrical and optical isolation. As expected, the tuning obtained was predominantly due to thermo-optically induced changes in the refractive index of the silicon waveguide core, in which most of the optical power in the guided mode was confined. The result was a substantial *red-shift* (i.e. to longer wavelengths) when several milliWatts were supplied into the cavity region of the device structure. In a second experiment, a finite length waveguide Fabry-Perot cavity with mirrors formed by limited 'thickness' PhC structures (e.g. four rows of holes in a hexagonally packed or triangular arrangement) was found to behave in a significantly different fashion from that expected, with a small *blue-shift* being produced when a much larger red-shift was expected. We have also applied thermo-optic effects successfully in both symmetrical and asymmetrical PhC channel guide Mach-Zehnder modulator structures – and have demonstrated respectable on-off ratios. Fairly straightforward modification of the device geometry could be used to convert such modulators into switches.

The fact that both red- and blue-shifts have been demonstrated indicates that the details of the whole device structure have an important controlling effect on its behaviour. Where the expected substantial red shift occurs, it may be attributed, for the example of an SOI-based structure, to the fact that the heat delivered into the device by the heater electrode reaches the silicon core - even though it must be transported through a silica buffer layer. Much the same argument applies in the case of the III-V heterostructures used in our first thermo-optically operated PhC Mach-Zehnder devices. In the case of the PhC-mirror waveguide Fabry-Perot cavity in SOI material, the blue-shift observed indicates that the somewhat thicker buffer layer, combined with a heater electrode that only partially covers the cavity region, gives substantially different characteristics. In this last situation, the heat generated by the electrode has presumably spread laterally - and a large part of the heat dissipation takes place in the silica buffer layer. The fact that part of the waveguide modal energy is transported in the upper and lower silica cladding regions also has greater significance. In this situation it should also be remembered that bulk silica itself exhibits an overall small negative temperature coefficient of optical delay, which arises from the fact that there is only a partial balance between the change of refractive index (which reduces as the material density decreases when thermal expansion occurs) and the greater path-length associated with physical expansion. For the case of silica fibre-optics, the thermal behaviour is of considerable importance for the exploitation of fibre Bragg gratings as precise frequency filters. For such grating filters, deliberate stress-optical behaviour may be imposed in order to compensate for temperature drift effects, via attachment of the grating region of the fibre to a bi-metallic strip.

Recent publications [1] describe how a silicon-silica multilayer mirror stack, considered as an example of a 1D PhC structure, can show substantially *athermal* behaviour in aggregate through the counter-balancing impact on the thermo-optic behaviour of stress-optical effects induced in the multi-layer deposition process. For the PhC-mirror waveguide Fabry-Perot cavity in SOI material, the large temperature change produced at the surface of the silica layer will also give rise to large stress-optical effects. These considerations also lead to a potentially important conclusion, that it should be possible to produce PhC or other types of device structure (e.g. photonic wire devices) in, for example, SOI waveguide material that exhibit substantially *athermal* behaviour, but that can still be tuned or switched via thermo-optic changes in the refractive index of the silicon core. The key requirement is that the heat *generation* region for thermo-optic operation be almost totally confined to the silicon waveguide core.

3. Thermo-optically tuned planar waveguide photonic crystal microcavity

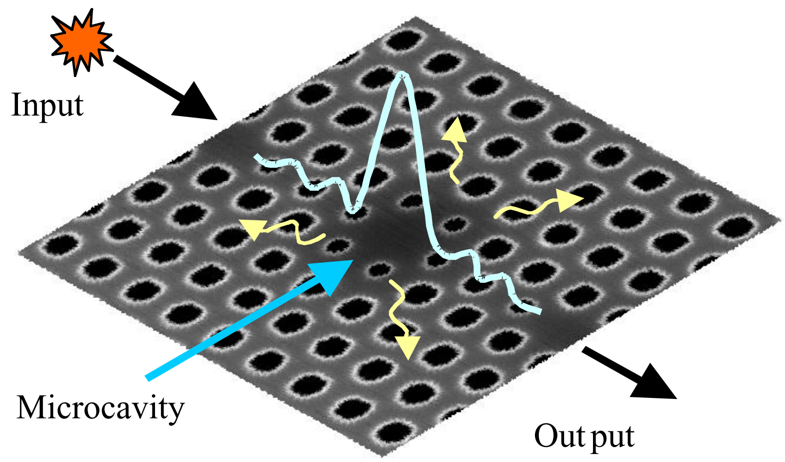

Fig. 1: Schematic of modified H2 microcavity based on a scanning electron micrograph. The direct feed input and output channel waveguides are shown, together size-tuned holes that provide cavity mode control and enhanced coupling into and out of the cavity [2].

Figure 1 shows a scanning electron micrograph of a photonic crystal channel-waveguide microcavity realised in silicon-on-insulator. The volume occupied by the resonant cavity mode is clearly potentially very small, as is partially shown by the results of a 2D simulation using FDTD modelling software. This device is strongly wavelength selective in its transmission properties. As shown in the Figure 1, with the input feeder and output W0.7 waveguides arranged for direct coupling, excitation of the appropriate cavity mode is effectively guaranteed. This mode may be described more precisely as a doubly degenerate hexa-pole mode. The Q-factor obtained with this type of cavity may be described as moderately high, being around 1000. Modifications to the waveguide configuration and cavity shape can readily increase the Q-factor by at least an order of magnitude. The specific form chosen may be described as a modified H2 arrangement in which six reduced diameter holes restrict the modal volume towards that of an H1 cavity and also provide a lithographic means of tuning the resonant frequency, via changes in their diameter. But displacing the centres of the holes from their standard position on lattice sites also provides a means of increasing the resonance Q-factor to values as large as 2000. It may be noted that a Q-factor of 2000 at an operating wavelength of 1500 nm corresponds to a nominal line-width of 100 GHz, i.e. a value which may be regarded as providing a starting point for a dense wavelength-division multiplexing (DWDM) capability. This point is made by way of arguing that achieving resonance Q-factors as large as 10,000 may be desirable, but rather than endeavouring to go much beyond that value it is considerably more important, from an engineering point of view, to consider how a specific resonance frequency can be obtained reliably and precisely, as well as the need to shape the transmission response to a more closely flat-topped form, with steeper skirts, enabling better channel separation and reducing the impact of uncontrolled fluctuations in the frequency.

In more detail, for the specific device structure evaluated in our experiments, a single-mode silicon-on-insulator planar waveguide was used, with a silicon core thickness nominally of 340 nm on a 3 µm thick buffer layer – and the basic 2D PhC lattice had a period of 420 nm, together with a nominal hole diameter of 250 nm. In-filling holes in the H2 cavity had a nominal diameter of 150 nm, with intermediate holes at the cavity input and output having a diameter of 210 nm. The PhC device patterning and electrode patterning were all carried out using direct-write electron-beam lithography (EBL). One-step dry-etching (RIE) was used to produce the PhC pattern and feeder waveguides, while lift-off procesesse were used in defining the electrode patterns. Controlling the resulting device properties indicates a need for hole diameter to be produced to a precision level of less than 10 nm. For thermo-optic tuning, the most important factor is that the thermo-optic coefficient of silicon is large, with a dn/dT value of 1.83×10^{-4} K^{-1}

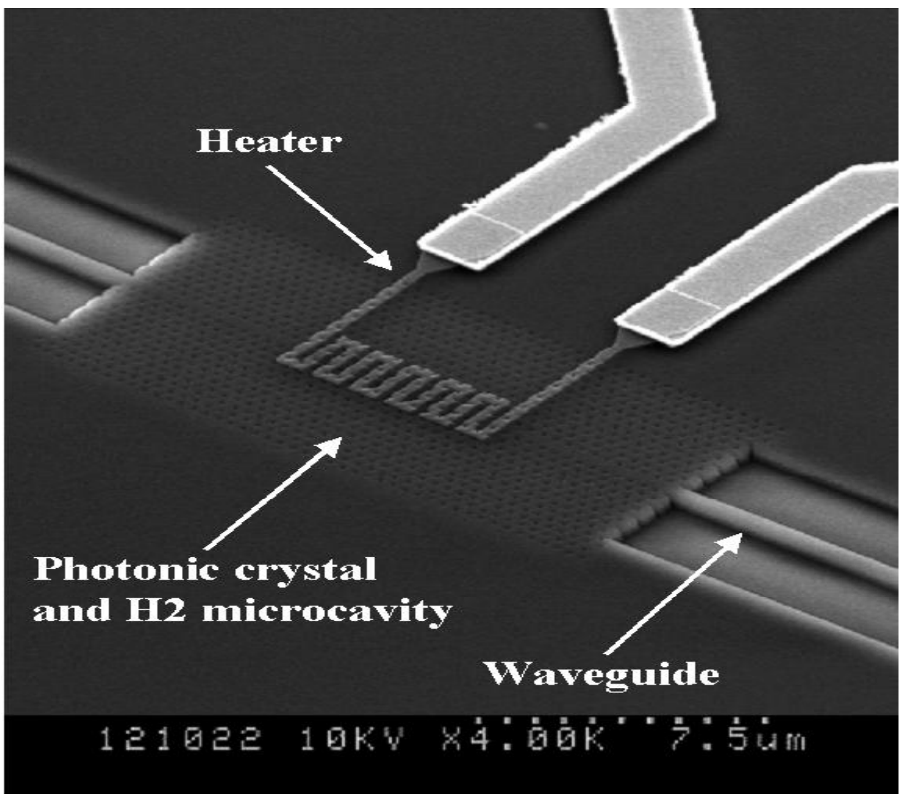

Fig. 2: Scanning electron micrograph of thermo-optically tuned PhC planar waveguide microcavity, with serpentine NiCr-film electrode pattern obscuring the actual cavity. Part of the gold feeder electrodes is shown, including the region of overlap with the the pads for the NiCr heater layer. The W0.7 channel guides are visible, aligned with photonic wire input an output waveguides. A silica buffer layer covers the SOI PhC structure, underneath the electrode patterns.

At an operating wavelength of around 1500 nm, obtaining a shift in wavelength of 5 nm implies a temperature change of approximately 150 K, assuming that the change is largely determined by the temperature of the silicon core. This relatively modest temperature change requires a substantially larger change in the temperature at the surface of the silica buffer layer, as was shown by thermal transport modelling. For the heater electrode, 50 nm of nichrome (NiCr) was used, together with gold feeder electrodes 150 nm thick. The deposited silica buffer layer was sufficiently thick (~250 nm) that it provided an adequate level of optical isolation - and physically prevented significant penetration of the heater metallization into the PhC holes.

Although the electrical power required to obtain the approximately 5 nm tuning level demonstrated in our experiments was modest at 9 mW, the area into which most of this power is delivered thermally is very small, i.e. approximately 5 μm^2. The thermal sensitivity of the device was more closely estimated to be about 500 $nm.W^{-1}$. It is clearly desirable to improve the device performance in various ways. Reducing the device area that must be heated and improving the delivery of the heat into the waveguide core will not only reduce the operating power required but also make a higher tuning rate (temporally) accessible, For the silicon-on-insulator waveguide system, the way forward has already been shown in work on photonic wire geometry Mach-Zehnder modulators where an appropriately doped silicon waveguide core has directly provided the ohmic heating element. The same approach can surely be adapted to a 2D PhC environment, provided that the interruptions in the silicon structure required to deliver the electric current and confine its flow can be implemented in a way which is compatible with retention of the PhC optical properties.

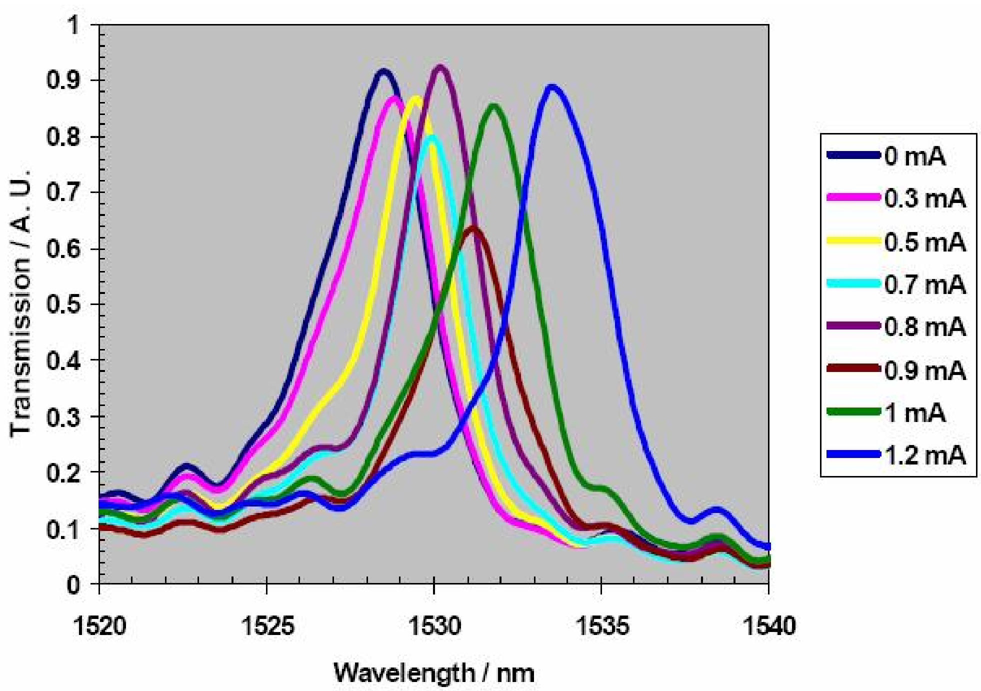

Fig. 3: Thermooptically tuned PhC microcavity spectral responses.

Fig. 3 shows the spectral response of the modified H2 micro-cavity with the heater current as a parameter. The intrinsic width of the serpentine heater electrode used was 300 nm and its measured resistance was 6.2 kΩ. It is worth remarking that, although we have not investigated the time dependence of the thermo-optic performance of the microcavity in detail, observations show clearly that more than one time constant is involved – and that the slowest effects have time constants on the order of a second. This behaviour is likely to be an indication of the time taken to approach a final temperature distribution across the silica part of the waveguide, as determined by thermal transport. The resulting situation in the silicon waveguide core, which has much better heat-conduction than silica, is a nearly uniform temperature distribution. But this temperature is determined primarily by the thickness of the silica layer above the waveguide core.

The device demonstrates an approximately 5 nm shift in the resonance peak wavelength when 9.2 mW is supplied by the heater electrode – over an obviously small area. The potential performance of this type of device is, however, clearly much better than demonstrated so far. Delivering heat by direct electrical heating of the core should be feasible – but will also require localised gaps in the PhC region to provide electrical separation. Estimating the number of resolved spectral positions that can be scanned provides a better characteristic measure of the shift of the resonance. In our case the value is small, being approximately two! Much larger values for the number of resolved positions become available if the resonance Q-factor is significantly enhanced. In real systems applications, e.g. in telecomms or datacomms, it may be the case that the absolute *range* of wavelengths that can be scanned is important, but the resolution within the specified range or ranges will still be important – and there will also be a requirement to improved the shape of the spectral response that could partially be solved by using a suitable coupled resonator arrangement.

4. Thermo-optic behaviour of a PhC mirror waveguide F-P cavity device

A second form of photonic-crystal based cavity device has been investigated as a candidate for thermo-optical control [3,4]. Here also SoI waveguides were used, but in a moderately wide (approximately 3 µm) and long (approximately 8 µm) structure with mirrors formed by finite length (4 rows of holes arranged hexagonally) PhC regions, as shown in Fig. 4, which also shows clearly the simple slab heater electrode that was used for this device. It is important, from the point of view of the device behaviour actually observed, to note that the NiCr electrode film was deposited over the top of a 300 nm thick silica layer acting as an optical buffer, that there were no PhC holes underlying the electrode film – and that the electrode metallisation did not cover the whole of the cavity spacer section, either along the cavity axis or transversely. This arrangement was sufficiently different in its total effect that, as indicated in Fig. 5, the effect produced by generating heat at the electrode was a relatively small peak shift to the *blue*, instead of the much larger shift to the *red* that was expected. The application of 2.25 mW of electrical power led to only a 0.06 nm blue-shift of the wavelength.

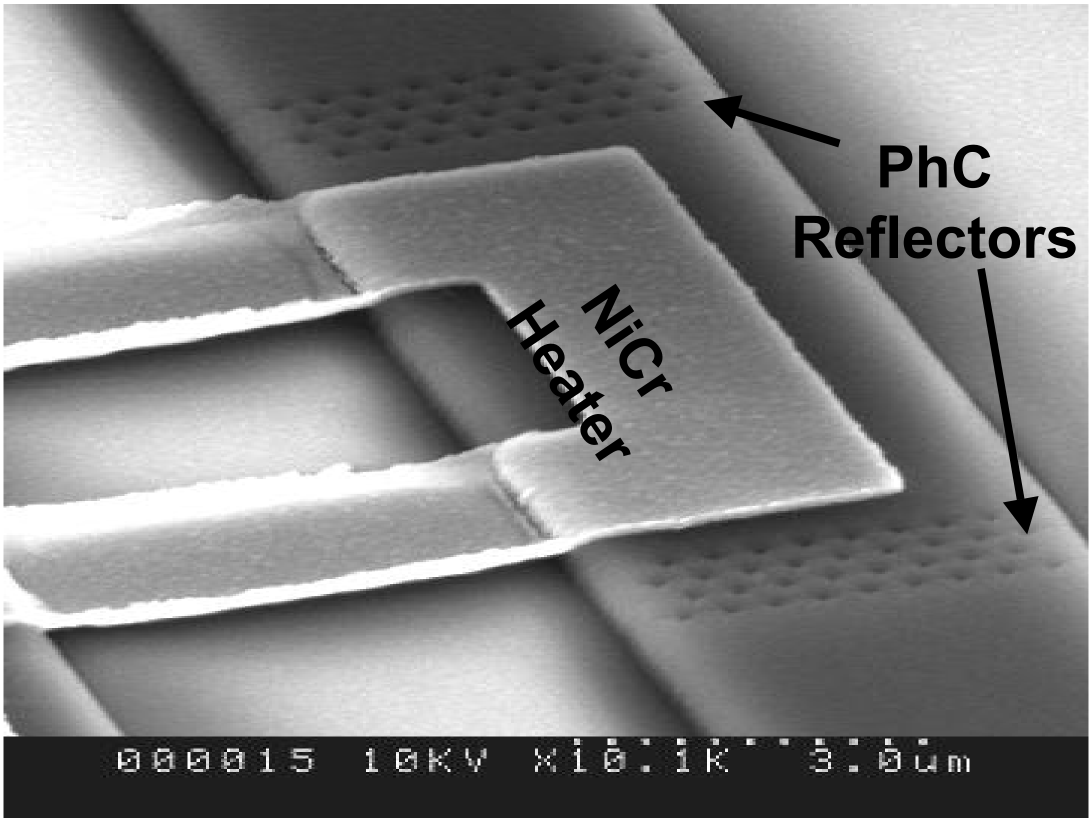

Fig. 4: Scanning electron micrograph of the PhC mirror extended Fabry-Perot micro-cavity realised in a section of SoI wafer, showing the NiCr heater film and gold feeder electrodes. The etched silicon core of the structure has been covered uniformly with 300 nm of silica deposited by plasma-enhanced chemical vapour deposition (PECVD), prior to deposition of the metallisation and formation of the electrodes.

The behaviour of this thermo-optic device also makes it appropriate to provide a remark concerning the computational analysis and design of photonic crystal device structures. It is clear in this case that understanding of the device requires a combination of 'purely' electromagnetic analysis and the incorporation of features that take account of additional effects. The thermal transport resulting from the application of heat at the electrode changes the refractive indices of the constituent materials according to the local temperature induced, simultaneously producing thermal expansion that is accompanied, in general, by non-uniform stress and strain distributions. Even where the base material - in this case a section of SoI wafer - is nominally unstrained, the subsequent processes used in forming the device structure may induce a substantial level of local stress and strain.

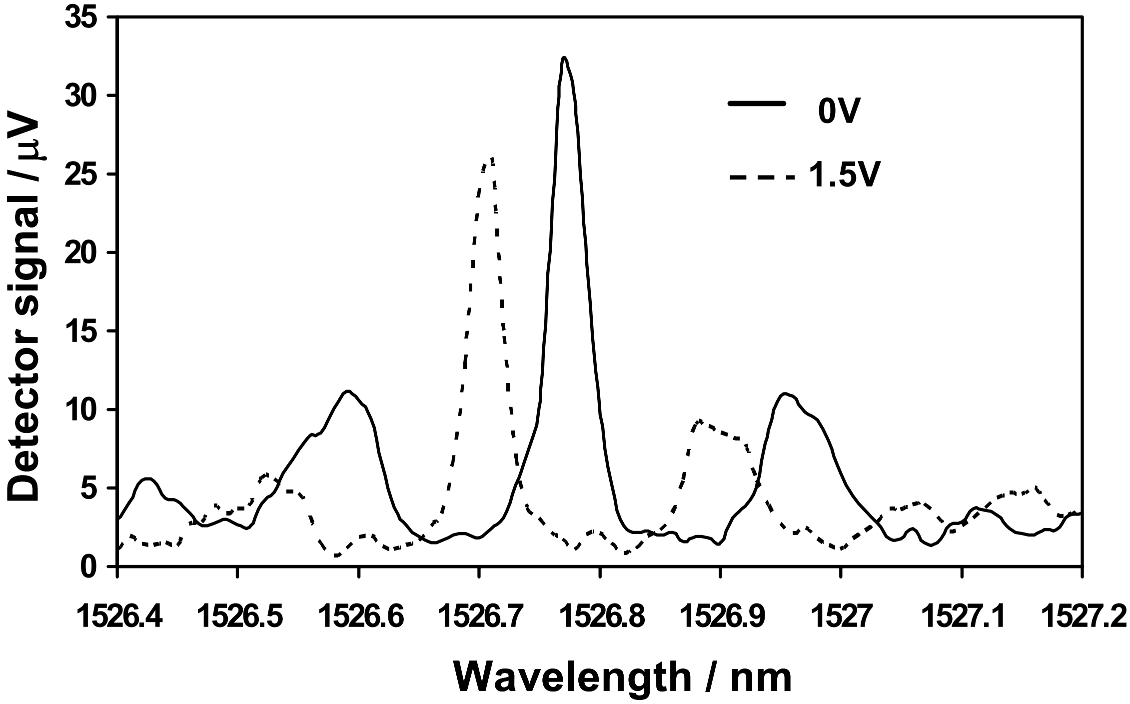

Fig. 5: Demonstration of blue-shift of the filter response when heater switched on at 1.5 V. Notice the small level of the shift produced, only ~ 0.06 nm. Individual spectral features observed are produced by double F-P cavity behaviour associated with sample ends.

5. Thermooptically operated PhC channel-guide symmetric Mach-Zehnder modulator

The photonic crystal Mach-Zehnder (MZ) structure [5,6] described in the conference presentation used progressive step-wise tapering of the PhC hole diameter in all diagonal branches of the structure, with successive diameter values of D_1 = 240 nm, D_2 = 260 nm, D_3 = 275 nm, D_4 = 290 nm and D_5 = 310 nm. Corresponding filling-factor values were in the range 35 to 50%, while the lattice constant was maintained at 390 nm. In this device the NiCr heating element had a total resistance of 8.2 KΩ. The bends and Y-junctions used to form the full M-Z structure were optimised separately using repeated simulations with 2D FDTD software. Typical results for the optimised transmission of a single bend and for a single Y-junction (into a single output) are shown in Fig. 6. The results show that close to 100% transmission is possible over several per cent bandwidths [7]. The resulting total transmission for the M-Z structure involves a convolution of the spectra of two bends in each arm and two Y-junctions, as well as the effects of any phase mismatch between the two arms of the interferometer.

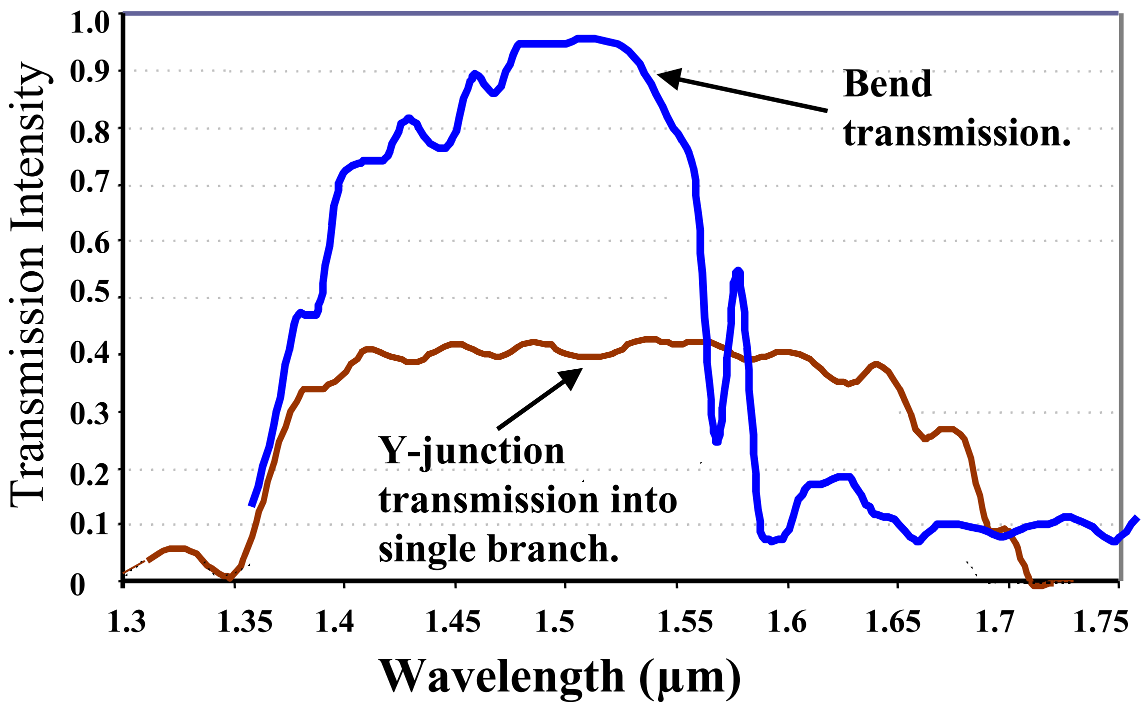

Fig. 6: Transmission spectra for PhC Mach-Zehnder device building blocks.

The Y-Junction optimisation involved the insertion of an additional hole in the junction region, on its axis, having a reduced diameter (160 nm) and being located at a position displaced from a lattice site towards the input by 50 nm. The 60^o bends were optimised by displacing symmetrically the two holes at the bend corners slightly towards the axis of the channel, along a local crystal axis. The epitaxial heterostructure forming the basic planar waveguide used upper and lower claddings with equal thicknesses (138 nm) having the composition $Al_{0.60}Ga_{0.40}As$ and refractive index 3.128, a 580 nm thick GaAs core with a refractive index of 3.379 – and a 2 µm thick $Al_{0.60}Ga_{0.40}As$ buffer layer on a GaAs substrate. A silica layer was deposited for pattern transfer, followed by patterning using a direct-write process in electron-beam resist, followed by two stages of dry-etch processing. A second silica layer was deposited to provide the optical buffer and then 150 nm NiCr was deposited and patterned using lift-off. Lift-off was also used to pattern the Ti:Au feeder electrodes. Very similar device structures were also realised in SOI with a 300 nm silica upper buffer layer, a 400 nm silicon core and a 3 µm thick lower buffer layer.

The results of Figure 7 show, in our view, a rather high level of agreement between computational and experimental results. Overall bandwidths of 70 nm at an operating wavelength of 1500 nm, with modest ripple, and clear reproduction of predicted features provide encouraging signs that the fabrication system and design philosophy that we are using has a useful level of robustness. Nevertheless, substantial qualitative and quantitative improvements are both desirable and attainable.

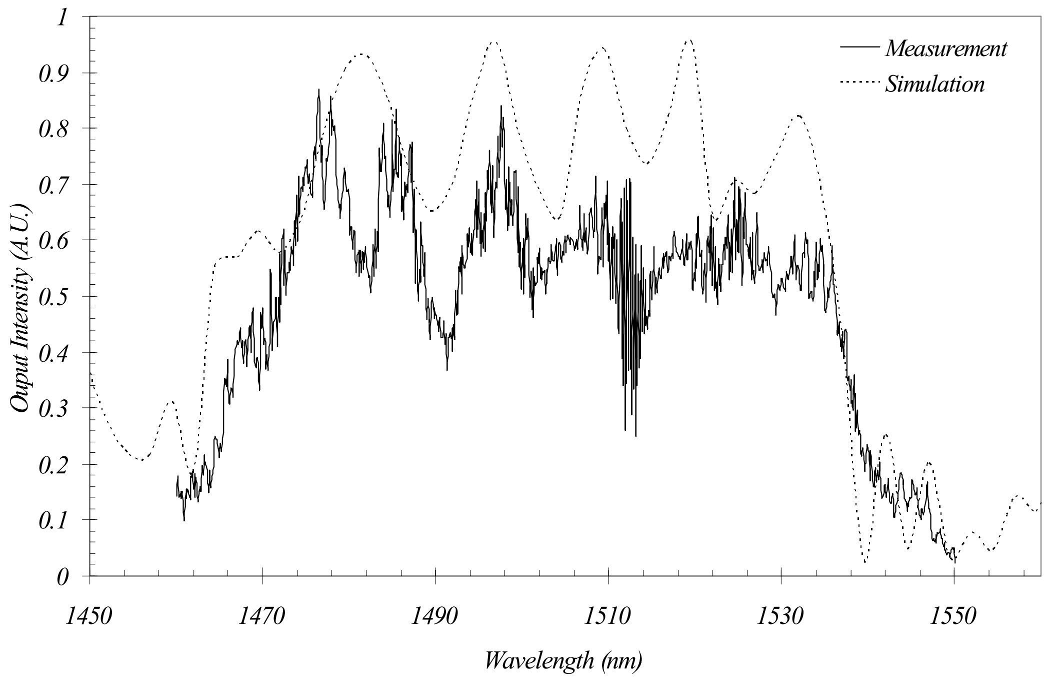

Fig. 7: Computed and measured transmission spectra for symmetric PhC channel-guide Mach-Zehnder device structure realised in AlGaAs/GaAs. (Dashed line – simulation. Bold line – measured).

6. Thermooptically operated PhC channel-guide asymmetric Mach-Zehnder modulator

We have also designed, fabricated and characterised an asymmetric PhC channel-guide Mach-Zehnder device. The key feature of the design was that only a minimal difference between the M-Z arm lengths was implemented (see Fig. 8), thus giving a relatively 'slow' wavelength variation and a reasonably complete null, because of similar propagation losses in the two arms of the structure. As expected, the device showed near-minimum transmission in the absence of thermo-optically applied bias and a transmission level that increased near-sinusoidally to a maximum value, followed by a decline back towards a minimum. Thermal power levels required in an SoI-based asymmetric device were of a similar magnitude to those used in the earlier symmetric GaAs/AlGaAs based heterostructure. This similarity can be ascribed in part to the fact that the thermal power was delivered through similar thicknesses of silica buffer layer.

Two different heater electrode geometries were evaluated and it was found that a narrower electrode that delivered thermal power more strongly confined to the actual channel guide region did indeed require less heater power. But a three times reduction in electrode width gave only an approximately 30 % reduction in the power required to achieve maximum transmission. Clearly there is significant lateral heat-spreading in the case of the narrower electrode, which might possibly be overcome by re-designing the structure – both through the introduction of physical breaks in the silicon core region and by improving the thermal transport from the heater electrode into the waveguide core, e.g. by reducing the buffer-layer thickness.

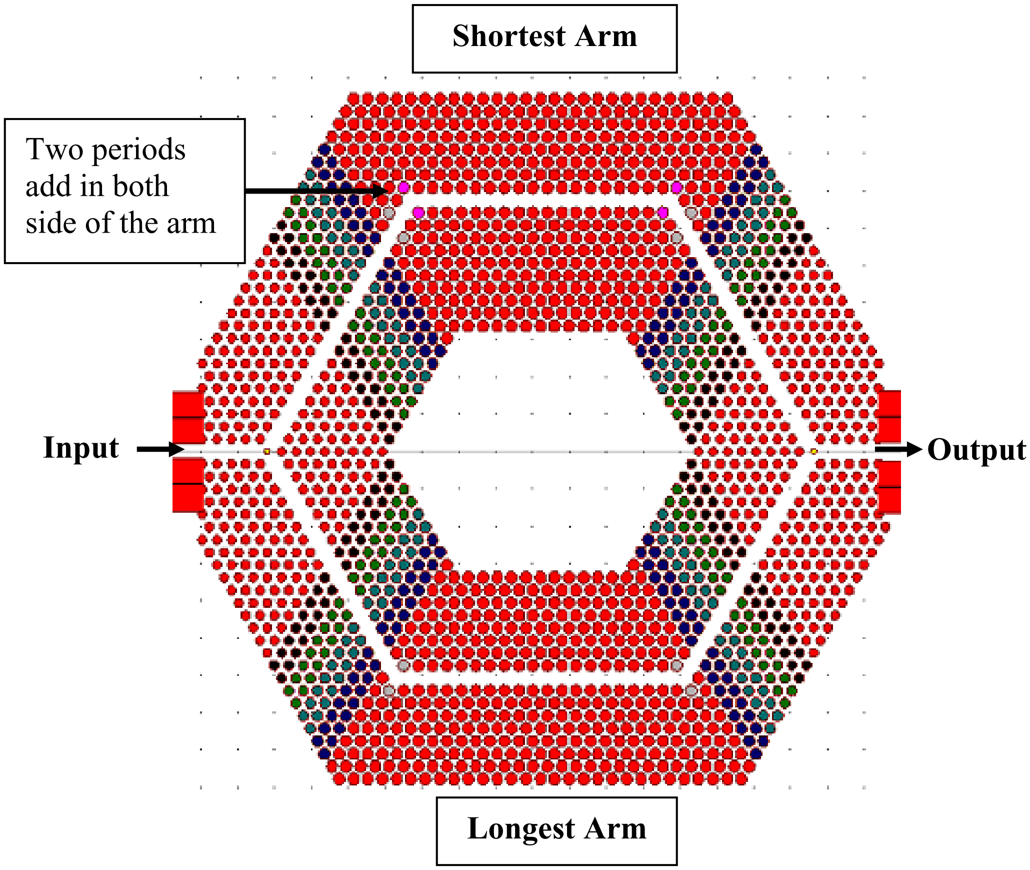

Fig. 8: Layout schematic for aymmetric PhC Mach-Zehnder structure. Careful counting of the numbers of hole rows indicates the presence of the arm length asymmetry.

Experimental results for the thermo-optic switching behaviour of PhC channel-guide *asymmetric* Mach-Zehnder devices have indicated an extinction ratio of around 14 dB in a device operating at λ = 1540 nm. The π phase-shift condition required for the maximum transmission condition was then achieved at heater power levels of 37 mW and 25 mW - for wide and narrow electrode configurations, respectively.

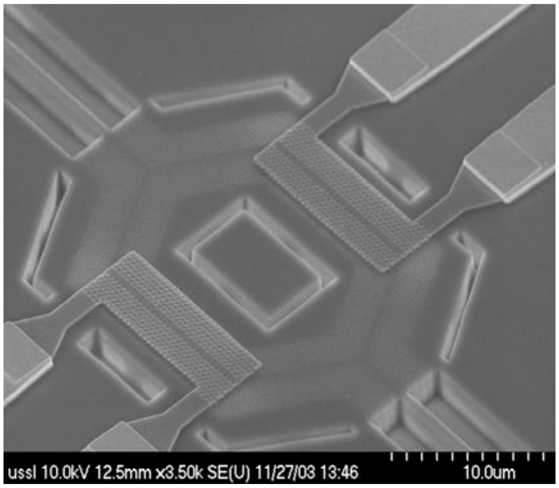

Fig. 9(a): Scanning electron micrographs of Mach-Zehnder asymmetric switch device, showing wide NiCr heater electrodes covering all of the PhC structure in each parallel arm.

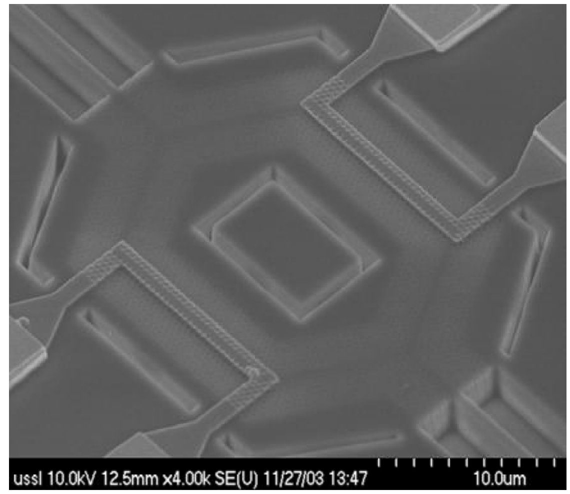

Fig 9(b): Scanning electron micrographs of Mach-Zehnder asymmetric switch devices, showing the narrow NiCr heater electrodes covering just the channel-guides.

7. Possibilites for producing faster thermooptically operated nanophotonic devices

Heating the silicon waveguide core in an SOI environment, through an electrically insulating buffer layer, is inherently limited by thermal transport. But some form of buffer layer is a requirement to provide optical isolation when a top heater electrode configuration is used. An electrode metallisation that is spaced by, for example, 200 nm of silica from a high index silicon core or weakly confined high index semiconductor heterostructure is close enough to have a noticeable effect. These effects include significant modification of the phase of guided light propagating over distances as small as a few micrometres – and reductions in the cavity Q-factor for moderately high-Q microcavities. One possible solution to the thermal transport problem is a partially electrically-conducting optical buffer layer, e.g. of ITO – as has previously been used, in $LiNbO_3$-based integrated optics. A shaped ITO layer could indeed provide the ohmic heating capability required, directly. III-V semiconductor heterostructure-based PhC and PhW devices could also exploit a direct heating approach, either using ohmic heating in the semiconductor or a directly applied heater electrode. Using direct heating of the silicon core, M.Geis and co-workers [8,9] obtained a 50 ns switching time in SOI photonic wire phase shifters and M-Z structures, at power levels in the 0.1 to 5 mW. Switching times less than 1 ns are now predicted.

8. Controlling the thermal situation: the need for simulation

As stated in the introduction, the refractive indices of semiconductors such as silicon, indium phosphide and gallium arsenide are strongly temperature dependent. Furthermore, waveguide formation processes such as epitaxial growth, wafer-bonding and (selective) thermal oxidation may induce large levels of stress and strain in the material system being produced - either deliberately or unintentionally. But stress-adjusted behaviour can greatly reduce the temperature dependence of PhC behaviour. It should indeed be possible to evolve both temperature-independent behaviour - i.e. uncooled/unheated operation -- and thermo-optical tuning. However, this desirable combination indicates the need for a major 3D computational design/optimisation exercise.

9. Conclusions

Their thermal behaviour and thermal control are unavoidably important aspects of the engineering of nanophotonic devices. With enough detailed design and analysis through computational simulation, together with knowledge and understanding of the fabrication processes, substantially *athermal* operation should be obtainable in planar photonic crystal devices. But, at the same time, the possibility of generating heat primarily in the high refractive-index waveguide core through ohmic heating also means that an athermal device structure can still be operated themo-optically. Fast modulation, switching and wavelength scanning (i.e. sub-microsecond) in devices operated at a few milliWatts of correctly applied electrical power are possible. Geis and co-workers [8,9] predict Gbit/s modulation rates with sub-milliWatt drive levels in photonic wire type device structures.

We have demonstrated experimentally that extended Fabry-Perot cavities in waveguides with 2D PhC mirrors are promising devices for DWDM wavelength selection in micrometric scale structures. Planar photonic devices that are certainly among the most compact Mach-Zehnder modulators and thermo-optically controlled micro-cavity resonators ever produced have been demonstrated.

Acknowledgements

The work described in this paper was supported in part by the EC project PICCO, by the EPSRC of the United Kingdom and by British Aerospace.

References

1. S.M. Weiss et al.' Temperature stability for photonic crystal devices', OPN,'Optics in 2004 special issue', p.35, (Dec 2004).
2. H.M.H. Chong and R.M. De La Rue, 'Tuning of photonic crystal waveguide microcavity by thermooptic effect', IEEE Photonic Tech Lett., **16**(6), pp. 1528-1530, (June 2004).
3. C. Ciminelli, F. Peluso, V.M.N. Passaro and M.N. Armenise, "Angular Response of Narrow Band 2D-PBG Guided Wave Filters, in 'Microresonators as building Blocks for VLSI Photonics', AIP, Vol. **709** , pp. 439-440, (2004).
4. C. Ciminelli et al, High-Q Guided-Wave Photonic Crystal Extended Microcavity, Post-Deadline papers, pp26-27, European Conference on Optical Communication, ECOC 2004, Stockholm, Sweden, (September 2004).
5. E.A. Camargo, H.M.H. Chong and R.M. De La Rue, '2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure', Optics Express, **12**(4), pp. 588-

592 (23 Feb 2004).
6. E.A Camargo, A.S. Jugessur, I. Ntakis and R.M. De La Rue, “Photonic crystal waveguide Mach-Zehnder structures for thermo-optic switching”, in Integrated Optical Devices: Fabrication and Testing, edited by Giancarlo C. Righini, Proc. SPIE **4944**, pp. 376-381, (2003).
7. I. Ntakis, P. Pottier and R.M. De La Rue, ‘Optimization of transmission properties of two-dimensional photonic crystal channel waveguide bends through local lattice deformation’, Jour. Appl. Phys., **96**(1), pp.12-18, (1 July 2004).
8. M.W. Geis, S.J. Spector, R.C. Williamson and T.M. Lyszczarz, 'Fast, < 1 Nanosecond, Thermo-Optic Phase Shifters and Switches in SOI', Integrated Photonics Research and Applications (IPRA) Conference, San Diego, paper IMB4, (11-13 April 2005).
9.M.W. Geis, S.J. Spector, R.C. Williamson and T.M. Lyszczarz, 'Submicrosecond, submilliwatt, silicon on insulator thermoptic switch', IEEE Photonics Techn. Lett., **(16)**, pp. 2514-2516, (2004).