2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure

Edilson A. Camargo[1, 2], Harold M. H. Chong[1] and Richard M. De La Rue[1]

1. Optoelectronic Research Group, Department of Electronics and Electrical Engineering, University of Glasgow,
Oakfield Avenue, Glasgow G12 8LT, Scotland

2. Instituto Tecnológico de Aeronáutica, Centro Técnico Aeroespacial, Praca Marechal Eduardo Gomes, 50, São
José dos Campos, 12228-901**,** *São Paulo, Brazil.*
camargo@elec.gla.ac.uk

Abstract: The realisation of a thermo-optically controlled symmetric Mach-Zehnder interferometer switch based on an AlGaAs/GaAs epitaxial waveguide structure operating at wavelengths in the region of $\lambda = 1550$ nm is reported. The device is based on a very compact two-dimensional photonic crystal channel waveguide structure. The measured and simulated transmission spectra for the devices are in good agreement. The π-phase shift switching power for the device is as low as 42 mW.

OCIS codes: (230.0230) Optical devices; (250.5300) Photonic integrated circuits

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1. Introduction

Photonic crystal (PhC) structures are now being widely used in the design and realisation of optoelectronic devices and have become an important platform for the development of new devices for integrated optics. One such device is the Mach-Zehnder interferometer, which can provide both switching and modulation.

By using a PhC channel waveguide structure the overall size of the optical devices can be reduced substantially **-** and PhC Mach-Zehnder interferometers are now being developed as a

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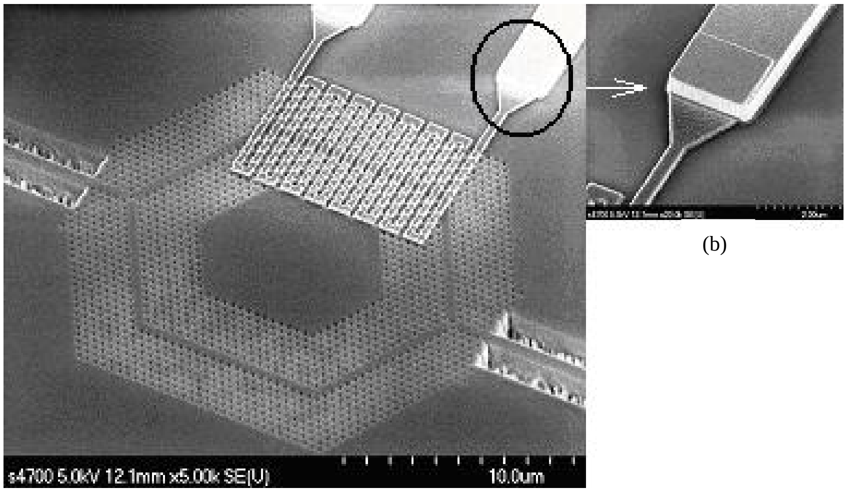
promising platform for actively controlled devices. A Mach-Zehnder interferometer operating successfully (in a purely passive manner) with an estimated 28% overall transmission using W1 channel waveguide was reported in [1]. An asymmetric Mach-Zehnder structure designed using a coupled-resonator W1 channel PhC waveguide has been reported [2] and another asymmetric PhC Mach-Zehnder structure was reported in [3], showing comparisons between different devices where the relative length of the arms of the Mach-Zehnder interferometer was changed.

This paper reports a 2D photonic crystal Mach-Zehnder interferometer structure in a switch that uses a thermally induced variation of the refractive index of the AlGaAs/GaAs epitaxial structure, for which the thermo optic coefficient is approximately 2.5×10^{-4} K^{-1}, as a switching mechanism. This device was fabricated to operate at λ = 1550 nm and the characterization used TE polarized light, i.e., with the optical wave electric field vector predominantly in-plane. The device that we have demonstrated uses thermo-optic switching via a heater electrode structure fabricated within a PhC environment - and we believe that this approach will be useful for further types of actively controlled device to be applied in optical integrated circuits.

2. Fabrication

The photonic crystal channel-guide devices were fabricated in an $Al_{0.6}Ga_{0.4}As/GaAs/Al_{0.6}Ga_{0.4}As$ heterostructure on a GaAs substrate. A hexagonal (triangular) PhC lattice of holes with a periodicity of 390nm was used. The upper cladding of the epitaxial guide structure was formed by a 138 nm thick layer of $Al_{0.6}Ga_{0.4}As$, the core was a 580 nm thick layer of GaAs and the lower cladding was a 2 μm thick layer of $Al_{0.6}Ga_{0.4}As$. The channel guide Mach-Zehnder structures were designed using PhC lattices with different filling factors in different parts of the structure, as described in detail in [4]. The Y-junctions use the filling factor of 35 % with a hole radius of 120 nm; the bends and the straight arms regions use a filling factor of 50 % with a hole radius of 150 nm.



(b)

(a)

Fig. 1. (a) Scanning electron micrograph of Mach-Zehnder switch device showing the NiCr heater on top of one arm of the structure. (b) Detail of interface between 150 nm thick NiCr heater layer and 300nm thick Au contact layer.

As shown by examining Fig. 1 carefully, a smaller hole with a radius of about 160 nm was placed in the centre of Y-junction as a matching defect to reduce reflection at the junction and avoid excitation of higher order mode propagation, as demonstrated in [5]. Reactive ion etching was used to define the photonic crystal structure and holes with a depth of 1 μm were achieved.

Thin film electrodes with a thickness of 150 nm were fabricated using evaporated nichrome lithographically defined by a lift-off process. Figure 1(a) shows the whole PhC Mach-Zehnder structure with the heater covering an area 5 μm wide by 12 μm along the straight arm. The total measured resistance of the heater electrode was about 8.5 KΩ. A 300 nm thick gold (Au) layer was used for the contact - and the interface between the nichome heater film and the Au contact can be seen in Fig. 1(b). A 250 nm thick silica (SiO_2) layer was deposited on top of the Mach-Zehnder structure. This layer was used to support the electrodes (partially blocking the PhC holes) and as an electrical and optical buffer layer between the heater electrodes and the PhC structure. The maximum power that could practically be applied using this heater arrangement was found to be about 90 mW.

3. Measurements

The device was characterized using TE polarized light from a tunable laser source over the range from 1460 nm to 1580 nm. The device was firstly measured with the heater electrode switched off and light was coupled into and out of the waveguide using an end-fire approach. The measured characteristics and the computer-simulated transmission characteristics obtained using a two-dimensional FDTD approach, as reported in [4], are shown in Fig. 2. The measurement and simulation show close agreement, with a measured transmission bandwidth of approximately 42 nm over the range λ = 1530 nm to λ = 1572 nm. This appropriately single-mode wavelength region was used for thermo-optic switching experiments. The peaks measured at ~1500 nm and ~1518 nm are associated with multimode behaviour that is observable experimentally and that occurs in the bends of the structure. The small peak in the simulation results at ~1485 nm is not significant and was apparently suppressed in the measured results. The enhanced transmission is possibly due in part to Fabry-Perot effects in the two arms of the structure.

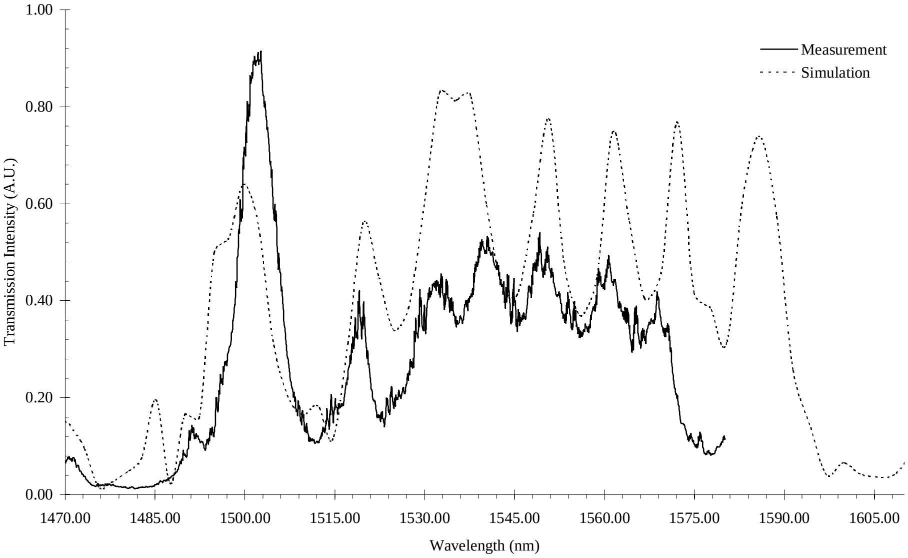


Fig. 2. Graph of transmission spectra: the dashed line shows simulation results and the bold line shows measured results. The y-axis is the normalised optical power output.

The oscillatory features visible in the transmission region have a periodicity that corresponds to a distance of 60 μm in the guide medium; a dimension that matches the length

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of the whole Mach-Zehnder structure. The smaller bandwidth achieved in the measured results, as compared with the simulation, may be due to wavelength-dependent losses associated with irregularities in the fabricated hole structure.

Figure 3 shows the thermo-optic switching behaviour of the Mach-Zehnder device at λ = 1540 nm, when the heater is switched on using a voltage controlled power supply. As the power is increased, there is an increase in transmission that peaks at 12 mW, instead of the zero power level that would apply for a perfectly balanced structure. This behaviour suggests significant imperfection in the device and indicates an important potential benefit of thermo-optic biasing. A π shift in the PhC Mach-Zehnder device was achieved at 42 mW as indicated by the transmission minimum. A quite modest redesign of the electrode structure to restrict further the area covered should enable this power value to be reduced considerably. The extinction ratio extracted directly from the ratio of the maximum to minimum values in Fig. 3 is -14 dB. The overall insertion loss calculated by taking into account the value measured for a 20 period long W1 PhC channel waveguide, in comparison with the Mach-Zehnder device, was -13 dB. This value also includes insertion losses in the tapered sections and 400 nm wide wire waveguide (approximately -6 dB) used to couple light into and out of the Mach-Zehnder device.

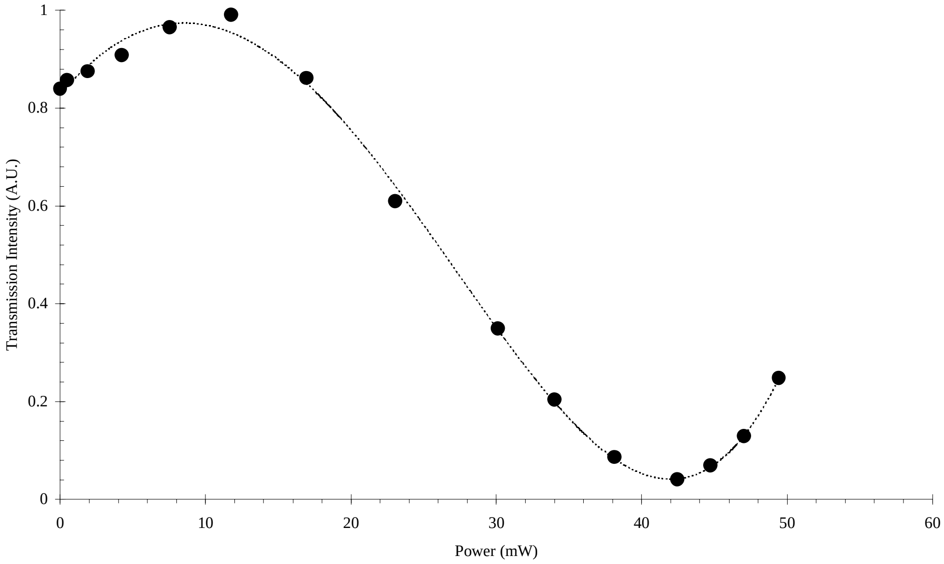

Fig. 3. Normalized optical power against electrical switching power measured at λ = 1540 nm**.**

The temperature increase required to produce a phase shift of π in a 12 μm long region of the Mach-Zehnder interferometer is given by Eq. (1) taken from [6, 7]:

$$\Delta T = \left(\frac{\partial n}{\partial T}\right)^{-1} \frac{\lambda}{2l_{active}} = 250°C \qquad (1)$$

A calculation of the thermal power required to produce this temperature difference, given the thermal conductivity of the AlGaAs that forms most of the epitaxial structure and assuming that the heat spreads slowly **-** with most of the vertical temperature drop occurring in the epitaxial structure, Eq. (2) may be obtained using for theoretical estimation which is also taken from [6, 7]:

$$P_{\pi} = \Delta T \sigma_{AlGaAs} \frac{(Wl)_{active}}{d} = 20mW \tag{2}$$

where, $\sigma_{Al_{0.6}Ga_{0.4}As}$ (17.08 $Wm^{-1o}C^{-1}$) denotes the thermal conductivity of the AlGaAs/GaAs structure, W is the active region width and corresponds here to the width of the W1 channel waveguide in the arm of Mach-Zehnder structure plus the widths of the two immediate lateral rows of holes, giving a total width of 1.06 μm, l_{active} is the active length and d is the thickness of the device (2.7 μm). The simplifying approximation is also made that the entire temperature drop occurs across the epitaxial layer.

The measured switching power of 42 mW measured is on the same order as the calculated value of 20 mW. However the calculated power neglects heat loss due to convection and radiation and does not use the thermal conductively of GaAs (~55 $Wm^{-1o}C^{-1}$), which is about three times higher than the value used for AlGaAs in the calculation. The experimental value of 42 mW also includes the 12 mW thermal bias required to achieve the in-phase condition at which the transmission maximum occurs. Additionally, the contribution to the phase shift from thermal effects of the SiO_2 buffer layer has been neglected because this contribution should be much smaller than the change for $Al_{0.6}Ga_{0.4}As$.

The switching time of the device should be comparable to values given in [6, 7], i.e., about 20 μs, since the thermal coefficient of GaAs is quite close to that of silicon. Recently there has been a report in [8] of a technique to enhance the heat exchange by applying a thermal bias to implement a high-speed thermo-optic modulator. The same approach should be applicable to the present device.

4. Conclusions

The realisation of what we believe to be first thermo-optic Mach-Zehnder interferometer switch based on a waveguide photonic crystal structure using an AlGaAs/GaAs epitaxial structure has been described. A device operating at λ = 1550 nm has been successfully fabricated and measured. The measured π-switching power is 42 mW (but this figure includes the 12 mW required to balance the device), so there is reasonably good agreement with the approximate calculated values. A substantial reduction in this switching power figure could be obtained by restricting the electrode coverage more closely to the channel guide region and by extending the electrode over a greater part of the selected interferometer branch through a simple re-design reducing the width of the electrode pattern. The measured and simulated transmission spectra of the Mach-Zehnder PhC device in the unswitched situation have been shown to be in good agreement, but with the measured bandwidth being slightly narrower. The fairly low switching power required for the PhC based Mach-Zehnder device has demonstrated its potential for use in future low cost and compact optical switches.

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