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Abstract

The HELIOS project is a European funded program which focuses on the development and integration of the different photonic and electronic building block components required to form high performance photonic circuits with a variety of functionality. One of the key photonic building block components central to most photonic applications is the optical modulator which is required to write data onto an optical carrier. Within the project two designs of carrier depletion based phase modulator are under development, together with a means of enhancing the modulation effect using slow wave and ring resonator based structures. In this work modulation results from the two phase shifters are presented along with passive results from related slow wave and resonator structures.

1. Introduction

In recent years silicon optical modulators based upon free carrier manipulation have emerged as an attractive means for high data rate transmission and have undergone a period of rapid development. Less than a decade ago devices generally reported bandwidths limited to the MHz regime, due to the relatively large device dimensions and the use of carrier injection to electrically control the effective index of the propagating optical mode. Many silicon based optical modulators reported recently use techniques which are not limited by minority carrier lifetimes (carrier depletion or carrier accumulation) and have demonstrated performances which are compatible with data transmission rates of 10Gbit/s [1-12] and 40Gbit/s [13]. In this work two designs of optical phase shifters in two different silicon overlayer thicknesses, 220nm and 400nm are reported. The devices are in each case based upon carrier depletion in diode structures and experimental measurements have demonstrated

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performance compatible with 10Gbit/s modulation for both devices. Also presented in this work are slow wave structures based upon corrugated waveguides and ring resonators within which the phase shifters are to be incorporated. Enhancement of the modulation effect through the use of slow wave and resonator structures is motivated by the prospect of reductions in the device footprint and/or drive voltage (and therefore power consumption).

2. 400nm Phase modulator

A cross sectional diagram of the modulator formed in waveguides of height 400nm is shown in figure 1. The modulator is based upon carrier depletion in a PIPIN diode. The other rib waveguide dimensions are 660nm (width) and 100nm (etch depth). These waveguide dimensions are designed for single mode propagation of the light through the device. Highly doped regions are positioned away from the waveguide to allow the formation of ohmic contacts to the diode whilst avoiding excessive modal overlap and therefore reducing optical loss. As a large part of the waveguide is not doped and the metallic contacts are deposited to the sides of the waveguide, low overall propagation loss is obtained whilst keeping a high modulation efficiency.

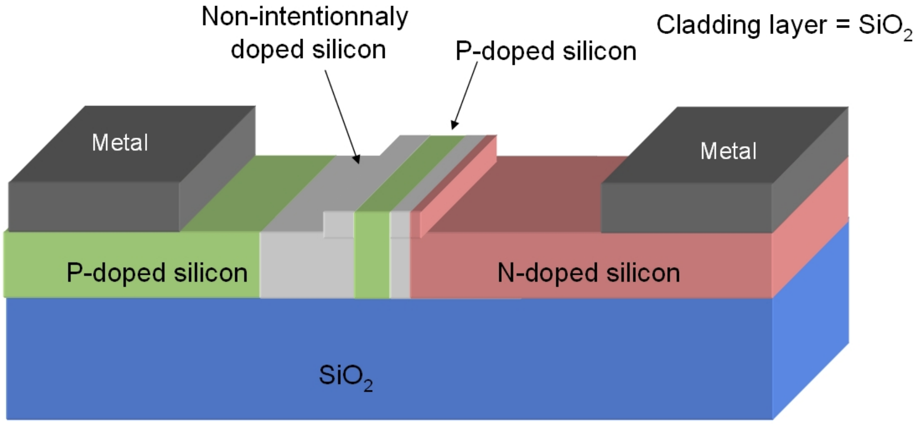


Figure 1 – PIPIN modulator in 400nm SOI

With no applied bias to the device the central p type doped region in the waveguide contains a certain density of holes which causes a reduction of the refractive index due to the plasma dispersion effect. Upon the application of a reverse bias to the device the holes in this region are depleted resulting in an increase in the refractive index within the waveguide and consequently a change in the phase of the propagating light. The configuration of this device is advantageous over vertical structures since the capacitance and access resistance is lower, a larger operation speed is therefore expected. The device is incorpoarted into an assymetric MZI to simplify device charateirsation. A typical output spectra of the MZI is shown in figure 2 and modulation bandwidths for two devices variants (electrode variations) is shown in figure 3. Bandwidths of 10 GHz and 15 GHz are achieved for the two variants which is sufficient for data transmission at 10Gbit/s.

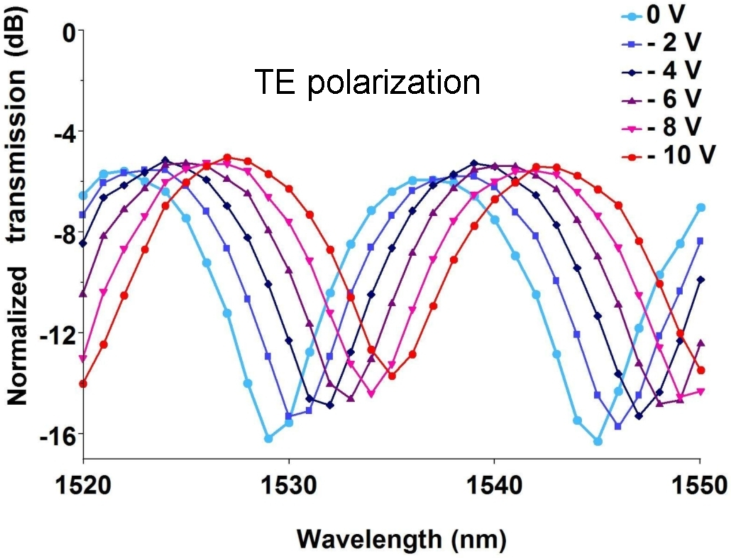


Figure 2 – Output spectra of the asymmetric MZI with different bias voltages

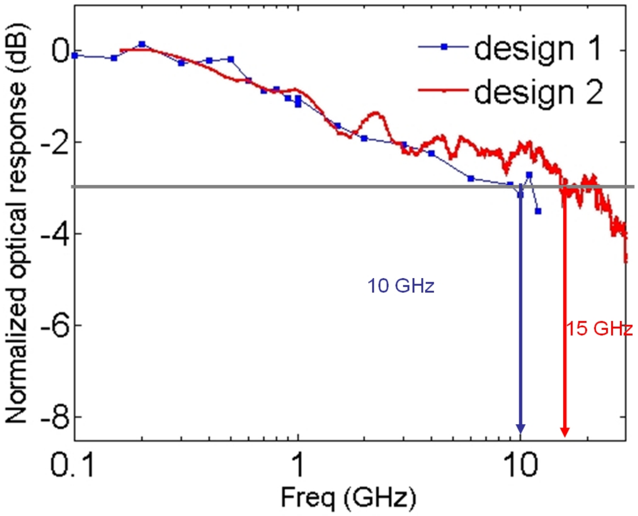


Figure 3 – Modulation bandwidth of the 400nm modulator

3. 220nm phase modulator

A cross-sectional diagram of the device formed in 220nm height waveguides is shown in figure 4. One key advantage of this device over those previously published in the literature is the ability to form the pn junction with a self-aligned process. Since this results in the junction occuring at the edge of the waveguide the doping concentrations are tuned in a way such that the depletion extends mostly into the rib waveguide.

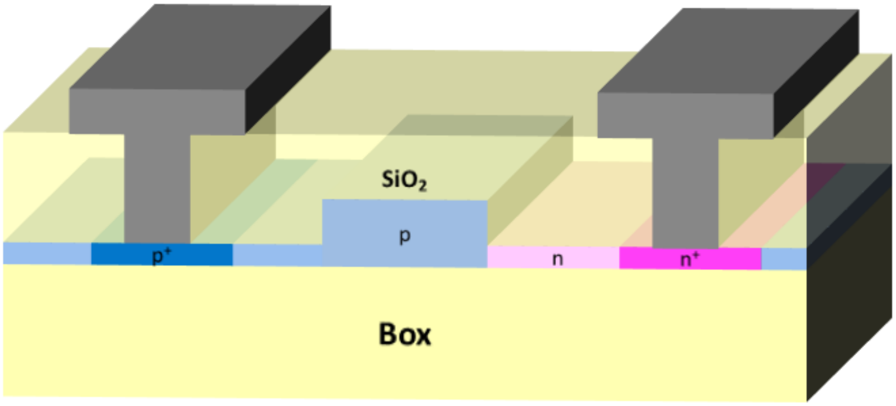


Figure 4 - PN modulator in 220nm SOI

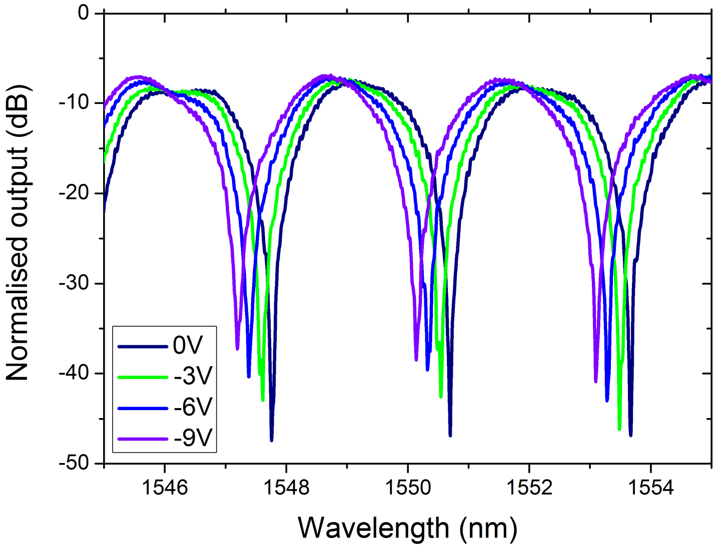
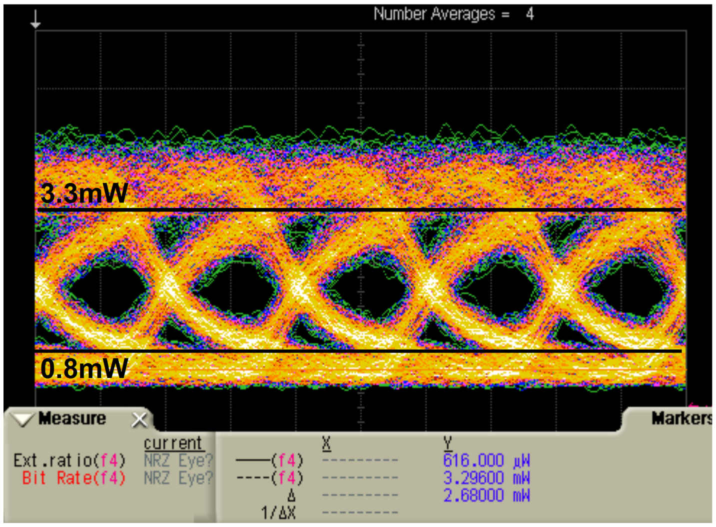


Figure 5 – Output spectra of the asymmetric MZI with different bias voltages

Similar to the 400nm device, highly doped p and n type regions are positioned far enough away from the waveguide to avoid significant optical loss and to allow ohmic electrical connections to the diode. In order to test the phase efficicency and to translate the phase modulation into intensity modulation the devices have been incorported into assymetric MZI structures. The device has been tested experimentally firstly by scanning the wavelength of the input light and monitoring the output power with different bias voltages, the results are shown in figure 5. From these results the phase efficiency can be estimated to be 8V.cm. Devices elsewhere on the wafer have reported modulation efficiencies down to 6V.cm. A large extinction ratio of the MZI of approximately 40dB can be observed which allows the potential for a large modulation depth. The device has also been tested at high speed and has demonstrated data transmission at 10Gbit/s with a modulation depth of greater than 6dB.



```
                current         X           Y
Ext.ratio(f4)  NRZ Eye?   ——(f4)  ---------   616.000 µW
 Bit Rate(f4)  NRZ Eye?   ----(f4) ---------   3.29600 mW
                              Δ   ---------   2.68000 mW
                            1/ΔX  ---------
```

Figure 6 – 10Gbit/s eye diagram with an extinction ratio in excess of 6dB.

4. 1D slow wave corrugated waveguides

One dimensional corrugated waveguide structures consist of a periodic variation of the waveguide width along the waveguide as shown in the images of figure 7 and 8. The main characteristic of such structures are their capability to decrease the group velocity of the propagating wave strengthening the interaction between the optical mode and the depleted electrons and holes. This has the advantage of significant reductions of the interaction length and/or the drive voltage. Improvement in device footprint can reach in practice up to 10 orders of magnitude depending of the selected group velocity, although these improvements come at the expense of increased sensitivity to fabrication tolerances and device temperature.

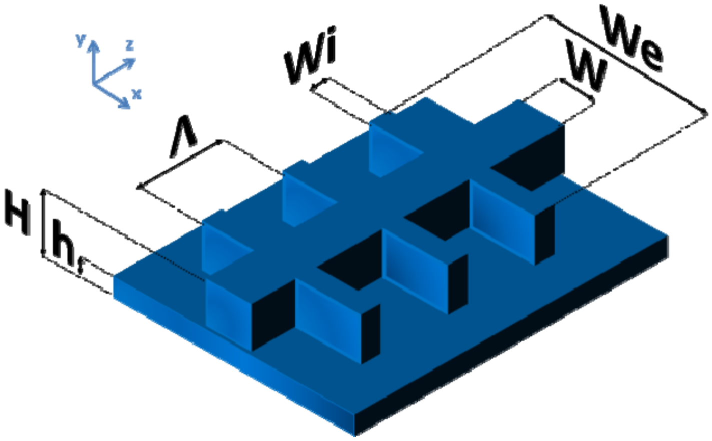


Figure 7 – Corrugated waveguide diagram

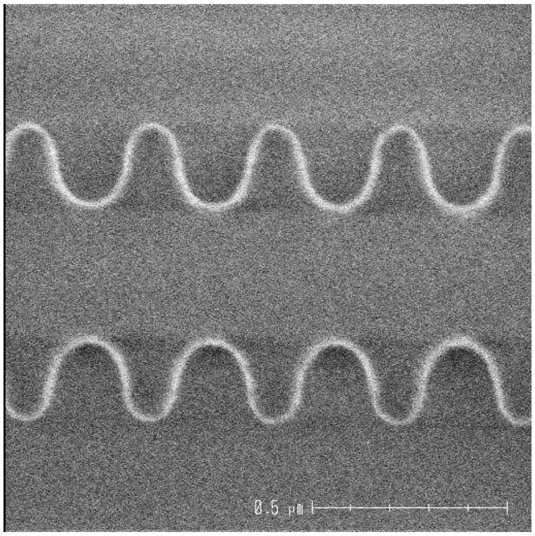


Figure 8 – SEM image of corrugated waveguide

The dimensions of the structure are carefully chosen to give a specific group velocity (and therefore enhancement factor) at a specific wavelength. Although the corrugated waveguide is designed with square features, in reality these become rounded in the fabrication process as shown in figure 8 which in turn has an effect on the optical response. In order to characterise the optical properties of the corrugated waveguide, the structures are incorporated into the arms of asymmetric MZI. A typical normalised spectral response is shown in figure 9.

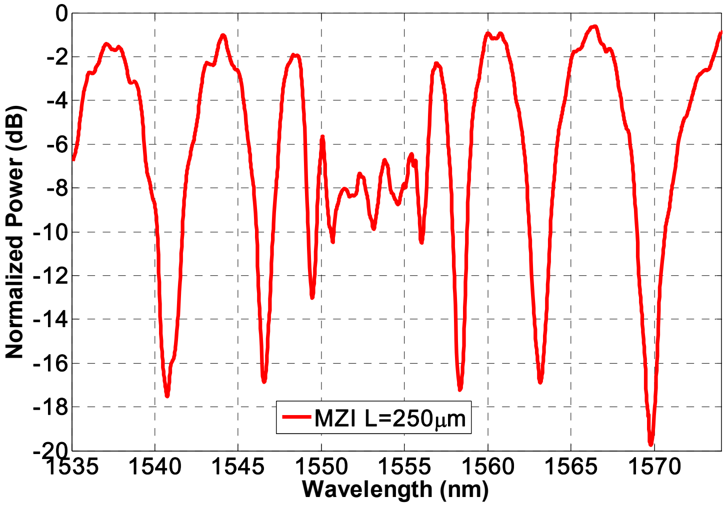


Figure 9 – Typical normalised spectral response of asymmetric MZI incorporating a corrugated waveguide

From this spectral response it is possible to calculate the spectral dependence of the group index which is shown in figure 10.

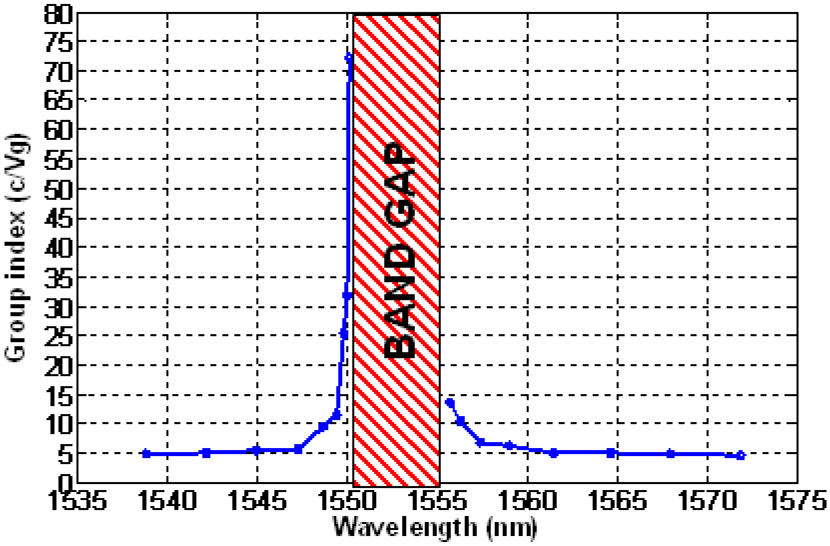


Figure 10 - Spectral dependence of the group index of a 1D slow wave corrugated waveguide

The maximum measured group index is n_G =72 corresponding to a minimum group velocity of V_G=0.014c and a slow-down factor of 20. Furthermore, the group index at exactly λ =1.55 µm is n_G =30, which corresponds to a group velocity as low as V_G=0.033c and a slow-down factor close to 10 [14].

However, slow wave regions usually feature a steep slope, limiting the useful optical bandwidth of the structure. To overcome such an issue, engineered corrugated waveguides featuring a relatively high group index over a wide frequency range have been proposed and demonstrated [15]. Namely, nearly constant group index as high as 13.5 over a wavelength range of ~14 nm has been experimentally demonstrated in a 50-μm-long waveguide as depicted in Figure 11.

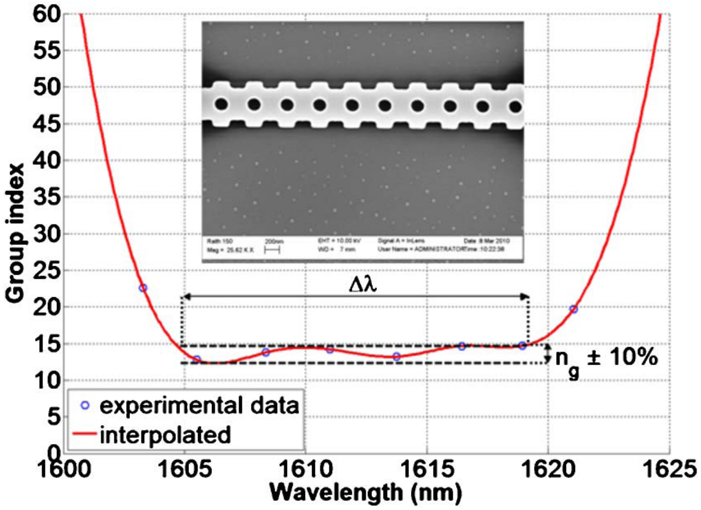


Figure 11 - Spectral dependence of the group index of a 1D engineered corrugated waveguide

5. Ring resonator based structures

Ring resonator based modulators which exploit a shift in the resonant wavelength to provide intensity modulation are not uncommon [1, 2, 4, 10]. They are attractive due to their compact size and relatively low power consumption. On the other hand they are again highly sensitive to temperature variations and fabrication tolerances. For practical application some means of temperature control will likely be required which contributes to the device complexity and power consumption. Fabrication tolerances are to some level an unavoidable characteristic of any fabrication facility. In order to achieve a large extinction ratio critical coupling of optical power into the ring is required. The amount of power required and amount of power coupled is dependant on the ring losses and the ring-waveguide separation, both are parameters which vary with fabrication tolerances. As a solution the phase response of the ring may be used with the ring resonator incorporated into a MZI. Figure 12 shows the different structures under investigation and figure 13 shows a SEM image of a single ring and MZI (REMZI-1).

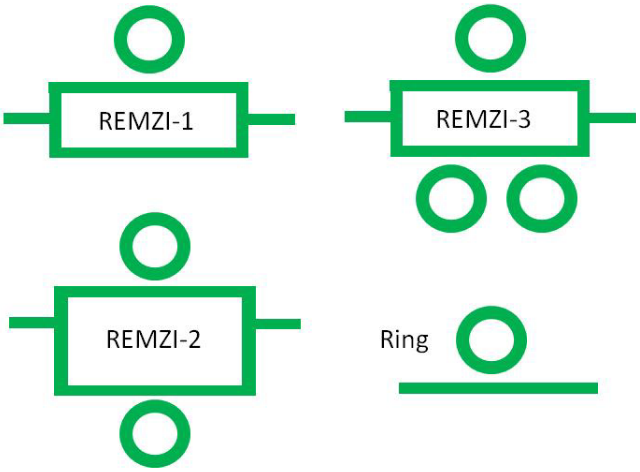


Figure 12 – Diagram of the different ring resonator sturctures under investiagtion

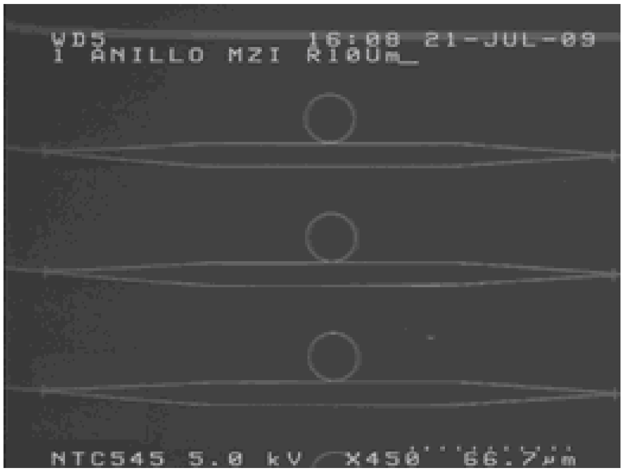


Figure 13 – SEM image of MZI with a single reing resonator

Ring enhanced MZI (REMZI) which exploit the phase response of the ring have the advantage that they do not need to operate at the critical coupling point to achieve a high extinction ratio, therefore a larger tolerance of the ring-waveguide separation and the ring losses is permitted. For example figure 14 shows the spectral response of the intensity based ring resonator and single REMZI. In both cases the ring and separation from the waveguide is the same. It can be seen from the response of the intensity based ring that it is not critically coupled. However when incorporated into the MZI an extinction ratio of approximately 10dB is achieved. In fact the extinction ratio of the REMZI decreases close to the critical coupling point due to mismatches in the optical power of each MZI arm. The purpose of adding additional rings into the structure is to balance the losses in the two MZI arms and threfore to improve the extinction ratio of the structure.

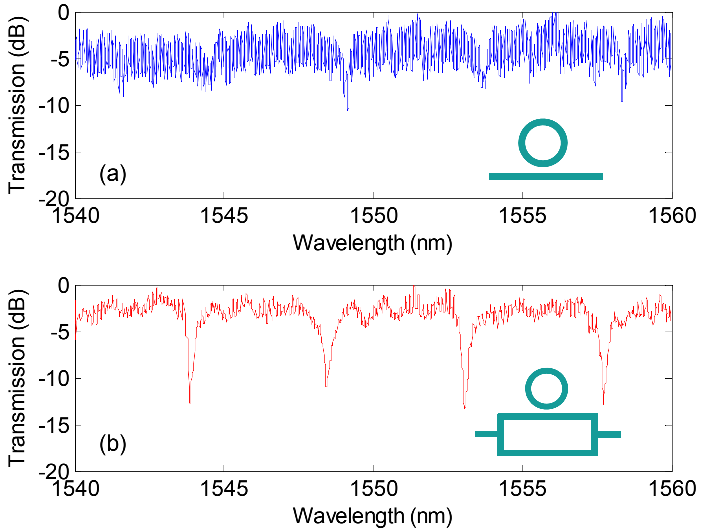


Figure 14 – Diagram of the different ring resonator sturctures under investiagtion

Conclusion

Two designs of optical phase modulator have been reported both demonstrating performances compatible with 10Gbit/s data transmission. Slow wave and ring resonator structures have also been demonstrated which can allow a reduction of the device footprint and/or drive voltage. Whilst those structures have obvious advantages they can sensitive to both temperature and fabrication tolerances. Depending on the requirements of the specific application of the modulation, the use of either a conventional or slow-wave and ring resonator approach may be preferred.

Acknowledgement

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