A ratiometric wavelength measurement based on a Silicon-on-Insulator directional coupler integrated device

(Invited paper)

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Abstract: A ratiometric wavelength measurement based on a Silicon-on-Insulator (SOI) integrated device is proposed and designed, which consists of directional couplers acting as two edge filters with opposite spectral responses. The optimal separation distance between two parallel silicon waveguides and the interaction length of the directional coupler are designed to meet the desired spectral response by using local supermodes. The wavelength discrimination ability of the designed ratiometric structure is demonstrated by a beam propagation method numerically and then is verified experimentally. The experimental results have shown a general agreement with the theoretical models. The ratiometric wavelength system demonstrates a resolution of better than 50 pm at a wavelength around 1550 nm with ease of assembly and calibration.

I. Introduction

The measurement of an unknown optical wavelength is a common measurement for many systems, either for test purposes or as an integral part of the operation of a system. Examples include the measurement of wavelength in a multichannel Dense Wavelength Division Multiplexing (DWDM) optical communication system, Fibre Bragg Grating (FBG) based optical sensing system and the estimation of the wavelength of lasers or tunable lasers during the manufacturing process. For a

DWDM optical communication system, wavelength measurement is indispensable in the accurate setting and maintaining of the transmitter's or of the monitoring tunable lasers' wavelength. For FBG based optical sensing systems, a cost-effective wavelength measurement scheme is very important in their successful commercialisation [1] .

The existing numerous wavelength measurement schemes can be divided into two main schemes, namely passive and active wavelength measurement schemes. Most of the existing passive schemes, employing wavelength sensitive optical devices, have a simple configuration and offer a high-speed measurement, but suffer from a limited resolution due to associated problems with the use of bulk-optic filter/collimation components and associated alignment stability or a limited wavelength range due to the spectral characteristics of the employed optical devices. The active schemes, mainly using wavelength-scanning technologies, which can achieve high resolutions, require much more complicated configurations and have a low measurement speed as compared to the passive schemes. The classic commercial instruments measuring the wavelength of light involves an interferometer or a monochromator, suffering from high cost and inherently slow measurement speed due to the mechanical motion involved.

A passive ratiometric wavelength monitor [2] offers a high-speed wavelength measurement with a smart footprint and a simple configuration. It consists of a splitter connected to an edge filter and a reference arm. The wavelength of the input signal is determined by the measurement of the ratio of the signal intensities. A ratiometric wavelength measurement scheme can be implemented with bulk devices , either an all-fibre based configuration [3] or integrated optical circuits [4]. Compared to bulk optical devices, integrated wavelength monitors have a low fabrication cost, compact size, high scalability and also benefit from a fast response and physical robustness. Examples include a multimode interference coupler, a system comprising three single-mode rectangular waveguides, a Y-branch with an S-bend structure, and a Y-branch with a multimode interference (MMI) structure [5].

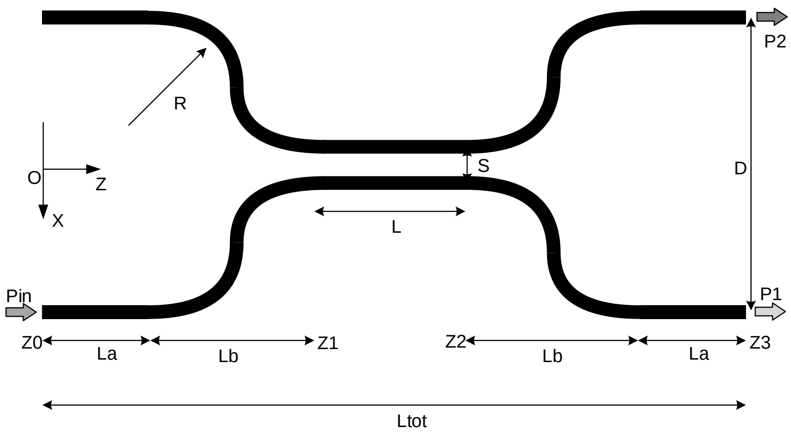
The directional coupler is a fundamental photonic building block which has been commonly used as power dividers [6], optical switches [7], filters [8] and modulators [9] in telecommunication applications. To date some research has been undertaken on the use of a directional coupler structure as an edge filter for use as wavelength monitor [10]. A directional coupler-based edge filter for wavelength monitoring can be directly designed from the waveguide parameters (geometry and refractive index profile) by calculating the spectral response of the directional coupler over the desired measurable wavelength range for each different interaction length with a given separation distance, i.e., by scanning the parameter-space (consisting of the separation distance and interaction length) in the 3-D case within a specified wavelength range, as shown in [11]. However, this method is time consuming, and also it only considers the central coupling region, whereas a complete planar lightwave circuit (PLC) implementation of a directional coupler should consist of an input waveguide region, a central coupling region and an output waveguide region. Therefore the entire PLC structure needs to be considered to take into account the couplings in the input and output waveguide regions.

Silicon-on-insulator (SOI) is an attractive platform for dense integration of optoelectronic devices, and a low-cost integrated optoelectronic circuit on SOI can be realized because the fabrication technology of optical waveguide devices based on SOI technique is compatible with mature CMOS technology [12]. Traditionally SOI consists of a thin silicon layer on top of an oxide cladding layer carried on a bare silicon wafer. With its silicon core and its oxide cladding, it has a high vertical refractive index contrast for better confining the fundamental guided modes in the silicon core. In addition, both the silicon and the oxide (normally silica) are transparent at telecom wavelengths of 1.3 and 1.55 µm. Therefore it can be a potential candidate to develop an SOI based integrated photonic device for telecom applications.

In this paper a simple design method is proposed (Section 2) to determine the required separation distance and interaction length of an SOI directional coupler to meet a desired spectral response as an edge filter device within an integrated wavelength monitoring system. The directional coupler design parameters, namely separation distance and interaction length, are solved with much less computation as compared to the parameter-scanning method described above in [13]. A numerical example is presented in Section 3 using a traditional beam propagation method (BPM) and the experimental verification is also presented in Section 4. In Section 5, a ratiometric wavelength measurement system using the fabricated directional coupler SOI integrated device as an edge filter is presented.

II. Theoretical design

The schematic of a simple ratiometric structure based on a directional coupler is shown in Fig. 1 and consists of an input waveguide region, a central coupling region and a output waveguide region. Two important parameters define the device: the interaction length (*L*) of two parallel waveguides and their separation distance (*S*) in the central region. For the input and output waveguide region, the separation between the two parallel waveguides increases gradually to 250 µm to allow connecting the directional coupler integrated device with the external coupling waveguides, normally standard singlemode optical fibres. The schematic cross section of the SOI integrated device is shown in Fig. 1(b). The desired spectral response as the ratio of the output power from the two arms of the parallel waveguides is presented in Fig. 1(c) and the corresponding ratio of the two outputs over the wavelength range is presented in Fig. 1(d). The wavelength of an unknown input signal can be determined by measuring the power ratio between the two output arms as shown in Fig. 1 (a), assuming a suitable calibration has taken place.



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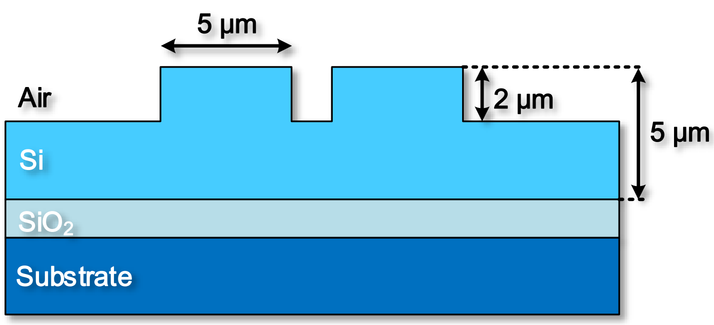

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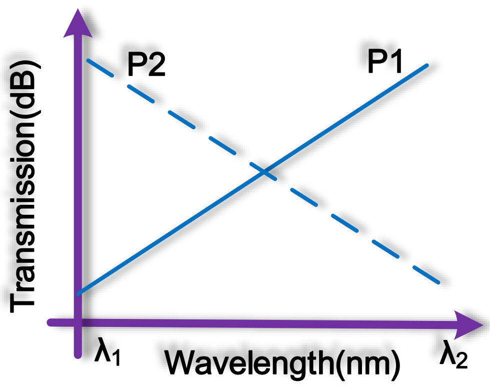

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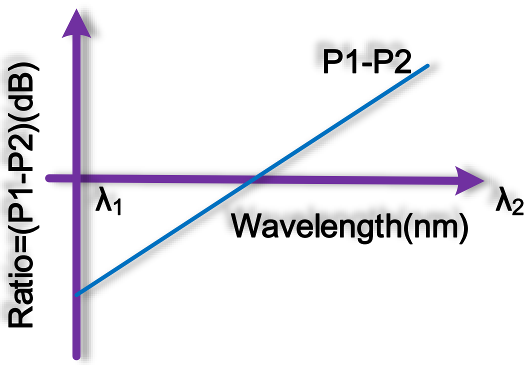


(d)

Fig. 1 (a) Schematic structure of an integrated ratiometric wavelength monitoring based on a directional coupler consisting of an input region, a central region and an output region; (b) schematic cross section of SOI waveguide directional coupler; (c) desired spectral response; (d) output ratio of the two arms over the wavelength range.

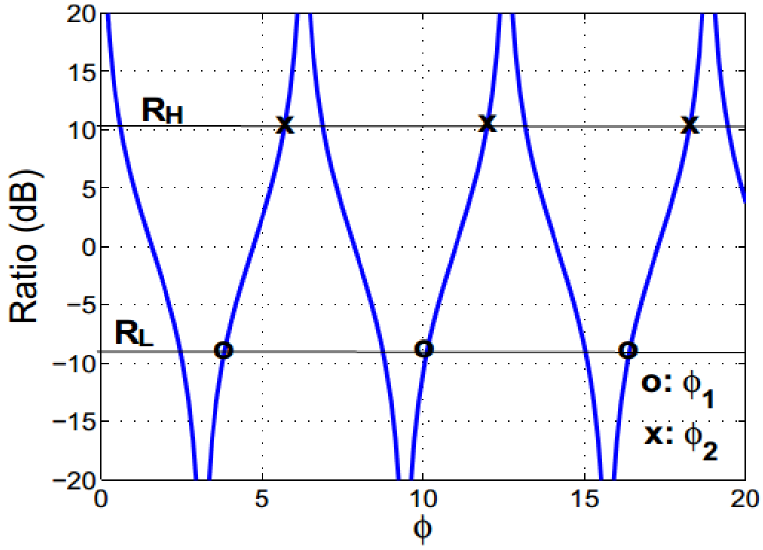


Fig. 2 Ratio of output powers as a function of the accumulated phase difference parameter.

A procedure to design the ratiometric wavelength monitor based on a directional coupler has been presented in our previous work [14] and it is adapted in this formulation. The relative output powers of the directional coupler according to an analysis of the local supermodes [11] can be given by

$$P_1 = \left(1+\cos(\phi)\right)/2 \tag{1.a}$$

$$P_2 = \left(1-\cos(\phi)\right)/2 \tag{1.b}$$

where $\phi = \phi_{in} + \phi_c + \phi_{out}$ is the total phase difference accumulated in the input region (ϕ_{in}), in the central coupling region (ϕ_c) and in the output region(ϕ_{out}). In the central coupling region of coupling length *L* (from $z = z_1$ to $z = z_2$) the phase difference is given by

$$\phi_c = \pi L / L_c \tag{2}$$

where $L_c = \pi / (\beta_+ - \beta_-)$ is the coupling length and β_+ and β_- are the propagation constants of a symmetric and an asymmetric supermodes, respectively. β_+ and β_- can be calculated using a numerical method such as a finite difference method {Ladouceur, 1996 #12}.

In the input and output regions (with a length of L_B, from $z = z_0$ to $z = z_1$ and from $z = z_2$ to $z = z_3$, respectively), the total phase difference can be evaluated using

$$\varphi_{in} = \int_{z=z_0}^{z=z_1} \left[\beta_+(z) - \beta_-(z) \right] dz \tag{3a}$$

$$\varphi_{out} = \int_{z=z_2}^{z=z_3} \left[\beta_+(z) - \beta_-(z) \right] dz \tag{3b}$$

It should be noted that at $z = z_0$ and $z = z_3$ the coupling between two waveguides is negligible $(\beta_+ = \beta_-)$, as the distance *D* between the two output waveguides is sufficiently large. Although the finite difference method [15] can be used to calculate β_+ and β_- at any positions in the input/output region in the z direction, it is time consuming. A method which utilizes a beam propagation method (BPM) can be more efficient [13].

The ratio between the two output powers is determined by the accumulated phase difference:

$$Ratio = 10 \cdot \log_{10}\left(P_1/P_2\right) = 10 \cdot \log_{10}\left(\frac{1+\cos(\varphi)}{1-\cos(\varphi)}\right). \tag{4}$$

and it is shown in Figure 2 as a function of the accumulated phase difference. A simple design method was envisaged to determine the separation distance (S) and the interaction length (L) associated to a specific directional coupler spectral response. The accumulated phase difference can be written as a function of separation distance (S) and a wavelength (λ) as:

$$\varphi = \varphi_{in}(S,\lambda) + \varphi_c(S,L,\lambda) + \varphi_{out}(S,\lambda) = \varphi_{in}(S,\lambda) + \frac{\pi L}{L_c(S,\lambda)} + \varphi_{out}(S,\lambda). \quad (5)$$

In the design of the ratiometric wavelength monitor, a chosen range of wavelengths between λ_1 and λ_2 corresponds to the desired ratio from R_L to R_H. Figure 2shows that values of accumulated phase difference φ_I and φ_2 for λ_1 and λ_2 correspond to the ratios R_L and R_H, respectively. There are series of φ_I and φ_2 values as depicted in Figure 2. Insertion of these values of φ and λ, separately, into (5) produces the two equations:

$$\varphi_1 = \varphi_{in,\lambda_1}(S) + \frac{\pi L}{L_{c,\lambda_1}(S)} + \varphi_{out,\lambda_1}(S) \quad (6.a)$$

$$\varphi_2 = \varphi_{in,\lambda_2}(S) + \frac{\pi L}{L_{c,\lambda_2}(S)} + \varphi_{out,\lambda_2}(S). \quad (6.b)$$

From eq. (6), the elimination of *L* allows to define an objective function *f* in terms of the variable S as:

$$f(S) = \frac{\varphi_1 - \varphi_{in,\lambda_1}(S) - \varphi_{out,\lambda_1}(S)}{\varphi_2 - \varphi_{in,\lambda_2}(S) - \varphi_{out,\lambda_2}(S)} - \frac{L_{c,\lambda_2}(S)}{L_{c,\lambda_1}(S)}. \quad (7)$$

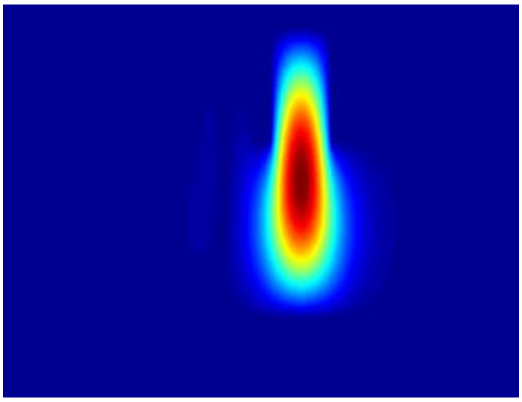
By using the chosen values of φ_1, φ_2, and utilizing (7), the optimum value of S can be obtained which corresponds to $f(S)$ = 0. Thus, the optimum value of *L* can be extracted from either of (6.a) or (6.b). Multiple values exist for the parameter pair φ_1 and φ_2, as seen in Figure 2, corresponding to multiple values of *S* and *L*. In practice, the values of φ_1 and φ_2 which yield a viable device size is chosen. And thus, to obtained the desired spectral response, the method proposed here only needs to calculate $L_c(S)$ and $\varphi_{in,out}(S)$ for the two wavelengths λ_1 and λ_2 rather than performing spectral response calculation for the whole range of directional coupler parameters in a conventional scanning method.

III. Numerical sample

A numerical example is presented here to demonstrate the design method and the ratiometric scheme. The refractive indices of the core and the cladding for an SOI waveguides are denoted as n_{co} and n_{cl}, respectively. To reduce leakage of the guided mode into the silicon substrate, we chose an oxide thickness of 1 µm. The height and the width of the core were chosen to be 2 and 5 µm respectively, in order to keep a good coupling between the adjacent SOI waveguide and also facilitate modal coupling between the SOI waveguide and the optical fibres. The coupler output was calculated assuming the height (h_x) and width (h_y) of the Si rib waveguide as $h_x = h_y = 5$ µm, $n_{co} = 3.5$, $n_{cl} = 1$ and the curvature radii for the both the input and output waveguides $R_d = 50{,}000$ µm. The calculated wavelength range is from 1500 nm to 1600 nm.

The device is designed to target a discrimination range $R_1 = -10$ dB to $R_2 = 10$ dB as depicted in Figure 2. The corresponding accumulated phase difference values are $\phi_1 = 3.754+j2\pi$ and $\phi_2=5.671+j2\pi$ with j = 0, 1, 2, and so on. The procedure given in the previous section provided the separation distance S = 1.6, 1.4 and 1.2 um with the corresponding interaction length of L = 19,840, 17,540 and 13,640 um, respectively. The viable device size was chosen from fabrication considerations, to minimise the separation distance and facilitate the deposition process: S = 1.6 µm and L = 19840 µm.

To independently verify the operation of the proposed design, a beam propagation method is used to calculate the whole spectral response with the designed structure within the wavelength range. Figure 3 shows the cross section views of the optical field patterns of the SOI waveguides when the operating wavelength is 1550 nm, for a coupling ratio of 1%:99%, 50%:50% and 99%:1%; the propagation distance are 4720 µm, 5905 µm and 7090 µm, respectively. Figure 3 shows that the coupling has occurred at the bending waveguide region. The accumulated phase difference between the two local supermodes in the input region is then obtained as $\phi_{in} = 0.13265$ ($=\phi_{out}$). Also, one can see that the relative output power of the directional coupler varies depending on the propagation distance and hence the coupling ratio varies.



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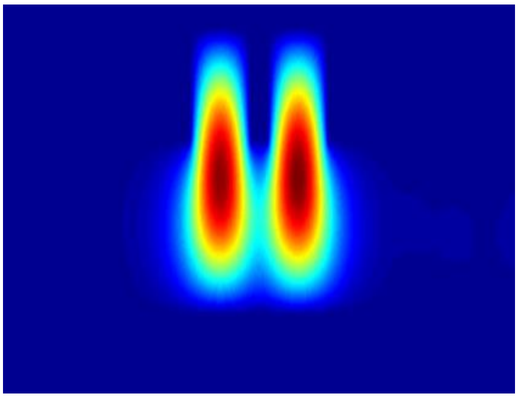

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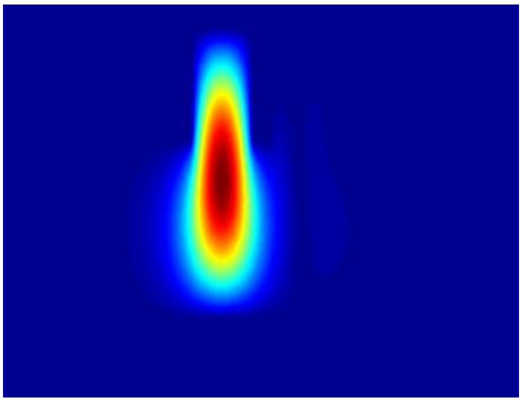


(c)

Figure 3. Cross section views of optical field patterns calculated by BPM when output power ratio is (a) 1%:99%; (b) 50%:50% and (c) 99%:1%.

The calculated spectral response is plotted in Fig. 4 from which it is clear that the discrimination range (from 1500 to 1600 nm) is -6.99 to -0.1 dB (for P_1) and -1.03 to -18.44 dB (for P_2) for the positive and negative slope edge filter, respectively.

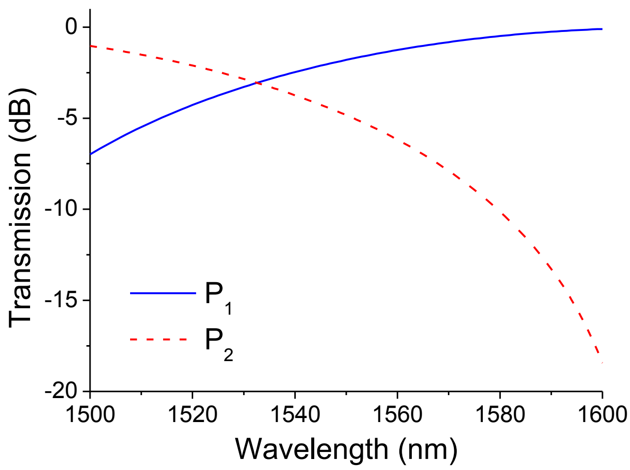


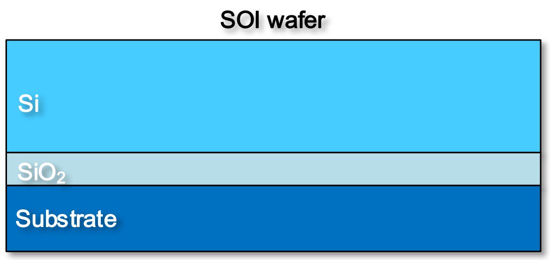
Figure 4. Calculated spectral response of the two arms of the device.

IV. Fabrication of SOI integrated device

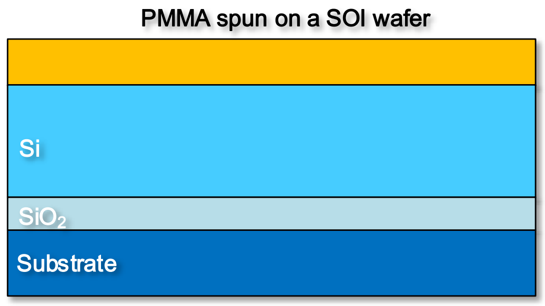
Devices were patterned on SOI Unibond wafers manufactured by SOITEC with 5 µm thick silicon on a 1 µm thick silica layer. The thick silica layer optically isolates the waveguide from the substrate, reducing losses due to substrate leakage. The wafer was polished on both sidesto reduce the device scattering loss.

The entire fabrication process of the SOI integrated directional coupler device is shown in Fig. 5. First, the wafer was cleaned by acetone, isopropyl alcohol, methanol and de-ionised (DI) water; then a dehydration baking process was carried out on a hotplate at 120 ºC for 3 minutes. A PMMA based e-beam resist was spun at 6000 rpm on the SOI wafer. The wafer was then prebaked on a hot plate at 180 ºC for a minimum of 5 minutes to vaporize the chlorobenzene and harden the resist, and the resulting PMMA thickness was circa 300 nm. The hardened resist was exposed lithographically using the JEOL JBX-9300FS Electron Beam lithography (EBL) system with a 20 nm resolution under the accelerate voltage of 10 kV. The electron dose was optimized so that the size of the patterned waveguide was equal to the targeted sizes. The exposed PMMA was developed in a 3:1 mixture of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) for 18 seconds and subsequently rinsed in

IPA for 18 seconds. The inductively coupled plasma (ICP) etching of the wafer was then carried out with the ICP-RIE (Plasmalab System 100, Oxford Instruments) system with an etch rate of circa 200 nm/min. The entire etching condition was carefully optimized to achieve a minimum sidewall roughness. After the removal of photoresist in O_2 plasma, the devices were cleaned and cut from the wafer and the devices were polished on both sides for measurements.



(a)



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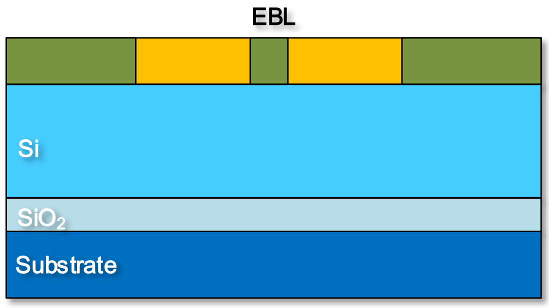

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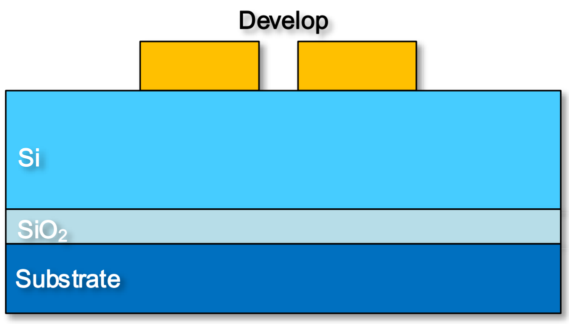

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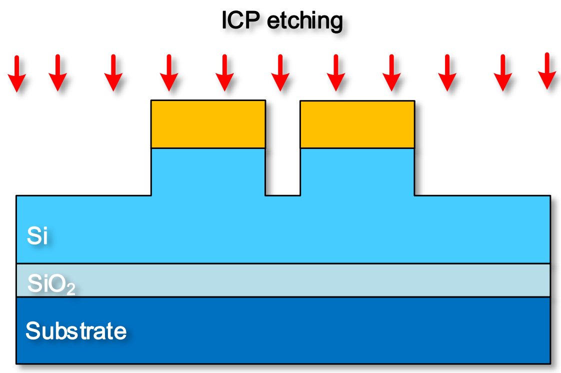

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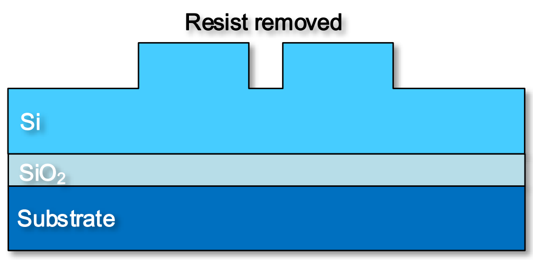
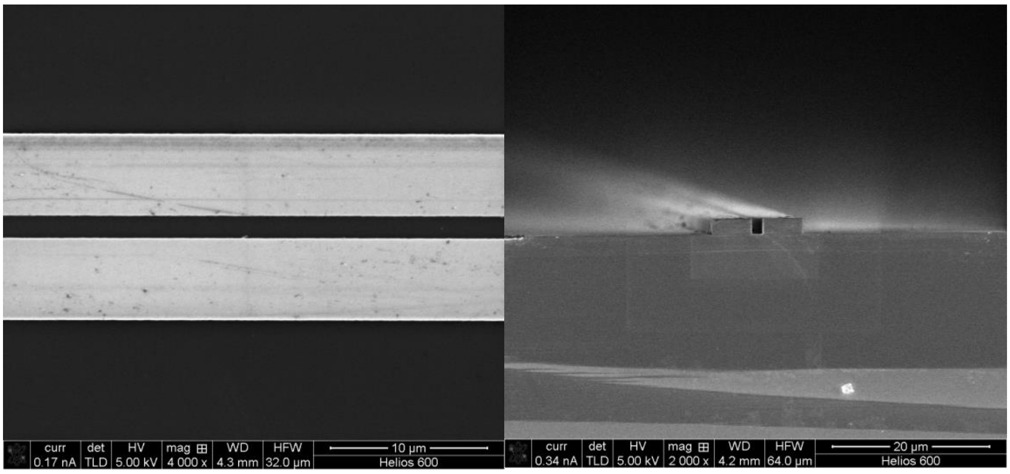


(f)

Figure 5. Fabrication process of the SOI waveguide directional coupler.

The SEM images of the coupling region of the fabricated SOI device are shown in Fig. 6. The figures have shown both a top view and a cross sectional view of the resulting dry etched features, indicating sidewall verticality and etching surface quality of the waveguides. The Plasmalab System 100 clearly demonstrated the capability of etching high quality SOI integrated photonic structures.



(a) (b)

Fig. 6. SEM images of the fabricated SOI integrated device.

V. Characterization of fabricated sample

The optical characterization was performed using a tunable laser coupled to the SOI integrated device via a polarization maintaining tapered fibre and a polarization controller. The output light from two arms was collected separately using two 20X objective lenses and two photodiodes placed at the ends of each arm to measure the optical power and hence the power ratio of the system. Fig. 7 shows the measured and simulated ratio results. The measured ratio data has a general agreement with the calculated results. From Fig. 7 one can see the measured results of the SOI integrated device are smaller than that for the device as predicted by the theoretical calculation. We note a circa 40.96% discrepancy existing on the discrimination range between the measured data and the simulated results, which are consistent on two different setups, thus pointing to either an imprecise refractive index used in the simulations, or more likely, variations in either the gap between the parallel waveguides or the slab thickness of the SOI, namely the manufacturing tolerances.

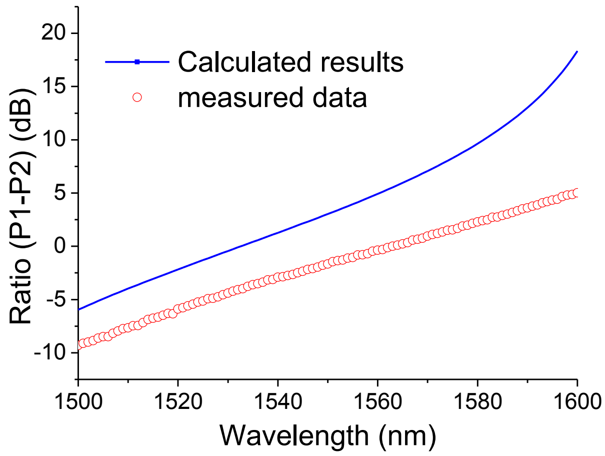


Fig. 7. Calculated and measured power ratio results of the fabricated SOI integrated device.

VI. Ratiometric wavelength measurement

Resolution for a ratiometric wavelength measurement system, i.e., the minimum wavelength shift it can detect in a range of practical applications, is an important performance parameter when the system is particularly used for monitoring a tunable laser or in an FBG based sensing system. According to the previous theoretical and experimental investigation [16] of the transmission response of an edge filter in a wavelength measurement application, resolution is restricted by a number of impact factors in the measurement system, including the slope of the transmission response of the edge filter, the measurable power range of the photodetector, the signal-to-noise ratio (SNR) of the optical source. In order to demonstrate the resolution of the wavelength measurement system based on the designed SOI directional coupler structure, the ratiometric wavelength measurement is performed by taking into account the above impact factors. The source wavelength is changed continuously around 1550 nm with a successive interval of 50 pm. For each tuned wavelength, the photodetectors outputs are sampled 100 times and the ratio of the photodetectors outputs is measured. The wavelength is incremented again and the process of sampling is repeated. The complete time series of the measured ratio values as a function of sample time is shown in Fig. 8. From Fig. 8, it is clear that the detectable ratio due to the wavelength tuning has a potential resolution at least equal to 50 pm, using the SOI directional coupler structure designed in this paper.

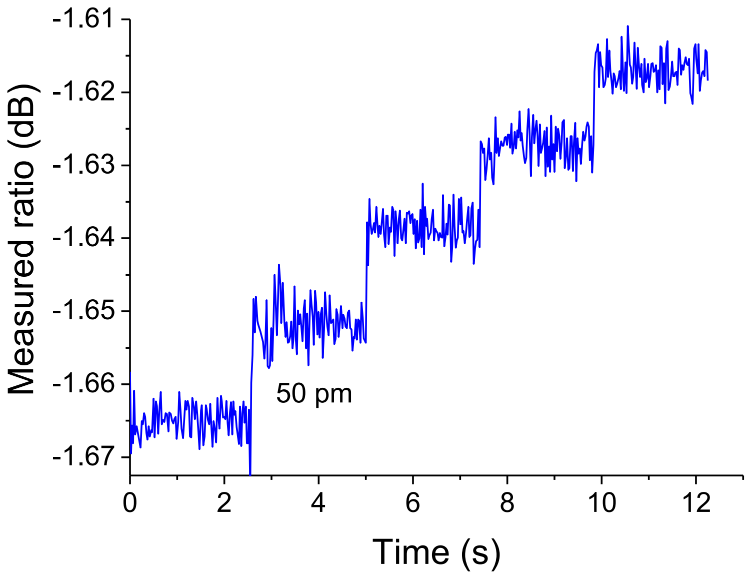


Fig. 8. Measured output of the ratiometric system as the input signal increases by 50 pm around the wavelength of 1550 nm.

As shown in Fig. 8, the wavelength is stepped by 50 pm every 2.5 seconds and one can also see that the clearly detectable change of the recorded output of the system shows a resolution of better than 50 pm, which is competitive as compared with some active wavelength scanning techniques, with the advantages of robustness and no mechanical movement. Also compared our previous work on optical fibre based edge filters [3,17], the advantage of this work is that silicon photonics is a new technology that should at least enable electronics and optics to be integrated on the same optoelectronic circuit chip, leading to the production of low-cost devices on silicon wafers by using standard processes from the microelectronics industry. Also the next generation of optical components needs to be low cost and compatible with high-volume manufacturing. Silicon photonics, using highly confined optical modes in silicon waveguide, appears as a unique opportunity to cope with this integration challenge.

VII. Conclusion

A simple integrated ratiometric wavelength monitor based on an SOI directional coupler integrated device has been designed theoretically and experimentally fabricated. The separation distance and interaction length of the SOI device are calculated according to the desired spectral response. The wavelength discrimination of the designed directional coupler structure has been demonstrated numerically and experimentally, and a ratiometric wavelength measurement has been also undertaken, a competitive resolution better than 50 pm for a rapid passive wavelength measurement with the advantages, such as a simpler configuration and low-cost has been shown as compared to existing ratiometric wavelength measurement systems.

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