Silicon Waveguides Based Ultra-Wide-band Filter for Raman Amplification

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Abstract An ultra-wide-band (UWB) filter based on silicon-on-insulator (SOI) multimode interferometer (MMI) couplers and a Mach-Zehnder interferometer (MZI) was proposed. It can select signal wavelength (around 1556nm) while removing pump wavelength (1440nm) which is 15.6THz away.

Introduction

Silicon-on-Insulator (SOI) wafers can be used for making compact low-loss (<0.1dB/cm) waveguide devices [1] including variable optical attenuators [2], waveguide autocorrelators [3], polarization beam splitter (PBS) [4], and polarization-mode converters [5]. Stimulated Raman scattering (SRS) in SOI waveguide [6-8] is a candidate for integrated optical amplifiers in future planar light circuit (PLC). Raman amplification in silicon and silicon based Raman laser [9] require a wavelength filter to separate the pump wavelength that is separated by 15.6THz from the signal wavelength (e.g. 1440nm pump for gain at 1556nm). Here we report the design, simulation, and measurement results of an ultra wide band (UWB) filter for possible use in an integrated silicon optical amplifier [7-9]. The filter is based on two multimode interferometers (MMIs) and a Mach-Zehnder interferometer (MZI), which provides phase delay to achieve constructive or destructive interference to separate widely different wavelength channels. The proposed device is simple and has potential for monolithic integration with other SOI-based optical devices [2-9] to eliminate the loss from connections of several individual components. The UWB filter has potential use in an integrated silicon waveguide optical amplifier, to combine or separate the pump signal (1440nm) and probe signal (1556nm) for monolithic implementation of a silicon Raman amplifier.

Design and Simulation

The proposed filter is based on an asymmetrical MZI design, as shown in Fig. 1. The MMI couplers act as 3dB splitters, with tapers at inputs and outputs to reduce insertion loss. The inputs, outputs, and delay lines for the device have waveguide widths of 4µm. In the UWB filter, the required conditions for the length difference between the two arms of MZI (∆L) are

\[ \Delta L = \frac{(2m + 1)\lambda}{2n_{eff1}} \]  
\[ \Delta L = \frac{2m'\lambda}{2n_{eff2}} \]

where \( m' \) and \( m \) are integers, \( n_{eff1} \) and \( n_{eff2} \) are effective indices at \( \lambda_1 \) and \( \lambda_2 \) respectively. We can find several pairs of \( m' \) and \( m \) satisfying the conditions of filter. In our design the ∆L for the lowest order filter is 2.68µm. In order to increase the width of the passband, we choose the shortest ∆L possible that allowed the desired wavelengths to fall within the passbands of the filter rather than using a ∆L which gave a nominally exact match in passband center wavelengths with the desired wavelengths.

Fig. 1 Schematic layout of the UWB filter.

The numerical analysis of the UWB filter based on the calculated ∆L from equation (1) and (2) for the wavelengths 1440nm and 1560nm is plotted in Fig. 2. These theoretical plots show that the MZI has a designed 0.1dB spectral full-width of 21nm around 1440nm and 24.9nm around 1560nm while 3dB spectral full-width of 100nm around 1440nm and 116nm around 1560nm when ∆L=2.68µm. Even allowing for a large 0.5µm tolerance in etch depth, the designed target wavelengths can fall within the 0.1dB band of the filter if the length of each arm of the MZI is less than 2.7mm.

Fig. 2 Simulated results of the normalized output power at Port-C and Port-D for different wavelengths input at Port-A.
We used a commercial beam propagation method (BPM) software to simulate the performance of the integrated filter. Different wavelength input signals (1440nm and 1560nm) are launched into Port-A to model both wavelength are launched into the UWB filter. The BPM simulation results of the SOI UWB filter are shown in Fig. 3. When 1440nm or 1560nm signals are coupled into Port-A, it comes out at Port-D or Port-C respectively.

Experiment, Results and Discussion
The fabricated filter was tested with uncoated cleaved facets. The device was characterized by using tunable laser (scanning from 1440nm to 1570nm), which was end-fire coupled into the waveguide via an optical fiber. The output light was collected by a cleaved single mode fiber and measured by a PIN photodiode connected to a 500 MHz digital sampling oscilloscope.

Fig.4 shows the output power at Port-D and Port-C for different wavelength scan from 1440nm to 1560nm at Port-A respectively. The filter has a 3dB spectral full-width of 100 nm around 1440nm and 116nm around 1560nm, which agree well with our simulation (Fig. 2). The output ports had about 20dB wavelength selectivity for 1440nm and 1560nm wavelength inputs respectively. The simulated wavelength selectivity was 25dB for 1440nm and 28dB for 1560nm respectively. We believe the difference in wavelength selectivity between experiment and simulation is due to surface roughness of the MMIs in the UWB filter, making the splitting ratio deviated from 3dB. The polarization dependence wavelength (PDA) measurements were also performed by having different wavelength scan of TE and TM polarization from input Port-A to output Port-C and Port-D, as also shown in Fig. 4. The polarization insensitive wavelength is at 1453nm and 1556nm. The maximum polarization dependence is 0.35 dB at wavelength of 1510nm. The ripples on the curves in Fig. 4 may be due to the beating between evanescent substrate modes and guided modes in SOI waveguide. The fiber to fiber insertion loss of the uncoated device was about 9dB, which includes input and output fiber-waveguide coupling losses, 3dB Fresnel reflection loss from the two uncoated facets of the device and the losses in the two MMI and any waveguide losses. The insertion loss may be significantly reduced with the use of improved mode-matching between the waveguide and the input and output optical fibers (for example via the use of tapers [2]) and having AR coatings on the waveguide facets.

Conclusion
We described the design, numerical analysis, fabrication and experimental measurement results of a UWB filter for possible use in a monolithic integrated silicon optical amplifier. The proposed device is simple, suitable for integration with other optical devices and has potential to be shrunk into small size due to the high refractive index contrast in SOI waveguide. The filter has a 3dB spectral full-width of 100nm at around 1560nm, with wavelength selectivity is about 20dB. The broad passband is suitable for multiple wavelength operation in WDM network. Narrower or specific-shaped passband can be achieved by using cascaded MZI filter.

Acknowledgements: This work was fully funded by RGC Earmarked Grant CUHK2050324.

References