Monolithically-integrated SOI-based planar lightwave filter for passive optical network applications

Serge Bidnyk[1], Ashok Balakrishnan[1], Matt Pearson[1], and Mae Gao[1]
Dazeng Feng[2], Hong Liang[2], Wei Qian[2], Cheng-Chih Kung[2], Joan Fong[2], Jeremy Yin[2], and Mehdi Asghari[2]

[1] Enablence Inc., 400 March Road, Ottawa, Ontario, Canada, K2K 3H4
[2] Kotura Inc., 2630 Corporate Place, Monterey Park, California, USA, 91754

Abstract – A monolithically-integrated design and fabrication of a silicon-on-insulator filter is described. The filter uses a combination of a cascaded Mach-Zehnder structure and a planar reflective grating to multiplex 1310 nm channel and demultiplex 1490 and 1550 nm channels for applications in passive optical networks.

I. INTRODUCTION

Recent mass-deployment of passive optical networks (PON) has prompted researchers to explore a variety of technological platforms and architectures to produce bi-directional transceivers in a cost-effective manner. Traditionally, transceivers have been manufactured using bulk optics. In the bulk optic approach, commodity discrete components, such as laser diodes, thin-film filters, and photodetectors are assembled into a common housing using active alignment and labor-intensive techniques. Subsequently, lasers, photodetectors, and thin film filters were adapted to enable passive optical assembly of bi-directional transceivers [1]. Most recently, many research groups have made attempts to eliminate the use of the thin film filter technology by leveraging wavelength division multiplexing (WDM) capabilities of the planar lightwave circuit platform. In particular, bi-directional transceivers have been realized in both silica-on-silicon [2-4] and InP [5] material systems.

The emergence of the silicon-on-insulator (SOI) technology for building planar lightwave circuits presents an intriguing research opportunity to exploit the wide availability of silicon foundries and high-quality low-cost substrates for the next generation of silicon-based transceivers. Several SOI guided wave optical devices and circuits have already been demonstrated [6,7]. The SOI technology offers tremendous potential for cost-effective filtering, routing, and active component integration.

In this paper, we report on the design of a monolithically integrated SOI filter that comprises two disparate WDM elements. The first element is a cascaded Mach-Zehnder structure designed to be process variation insensitive and used as a coarse WDM splitter. The second structure is a planar reflective grating for fine WDM processing [8]. The two structures were combined into a monolithic SOI chip and successfully fabricated using CMOS-compatible SOI processes. The performance of the combined filter is discussed.

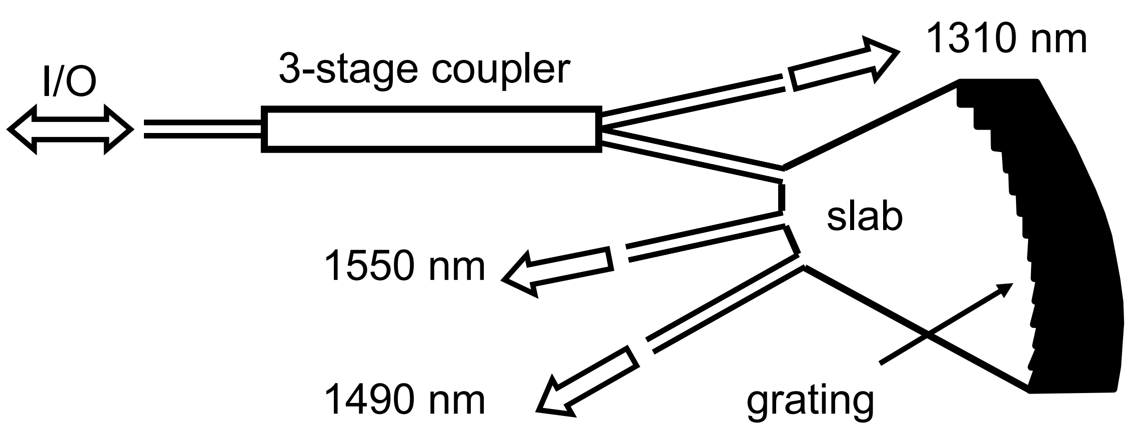

Fig. 1. Architecture of bi-directional PON transceiver.

II. DESIGN AND FABRICATION

In PONs, there are three wavelengths that are used for bi-directional data transfer. A service provider delivers an analog RF video signal in a broadcasting mode through a 25-nm-wide channel that is transmitted at a wavelength of 1550 nm. Digital data is sent to the end user though a 20-nm-wide channel at 1490 nm, usually time-division multiplexed among as many as 32 users. The end customer uses a broad transmission band around 1310 nm to send data back to the service provider. The end user relies on inexpensive uncooled lasers to send optical signals, thus requiring a 100-nm-wide transmission window at 1310 nm.

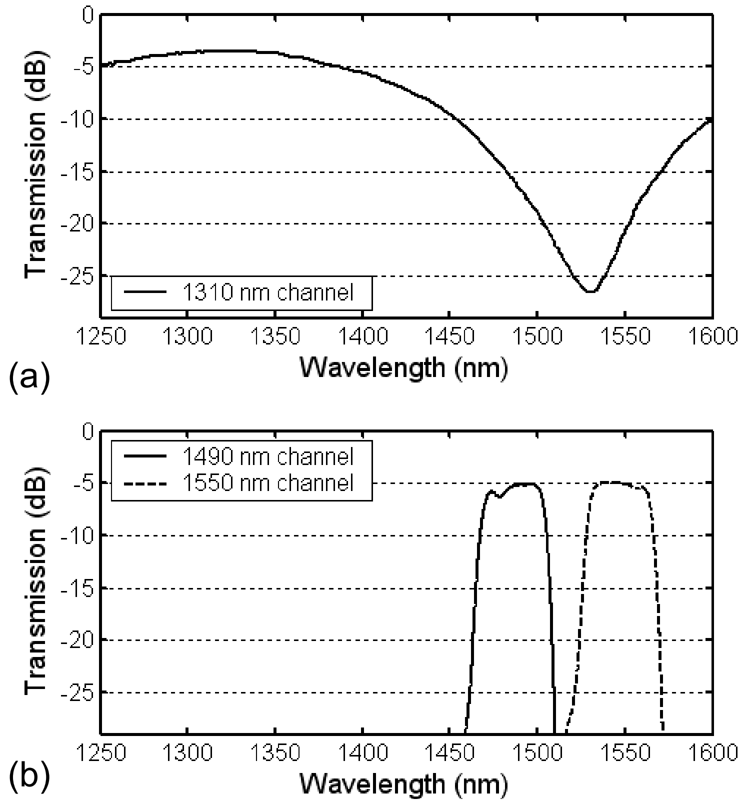

Fig. 2. (a) Spectral transmission of the 3-stage coupler for the 1310 nm channel (b) Combined response of the coupler and planar reflective grating for the 1490 nm and 1550 nm channels.

In order to meet these specifications, the architecture of the filter was chosen to comprise a coupler monolithically integrated with a planar reflective grating, as shown in Fig. 1. The coupler comprises 3 stages of Mach-Zehnder interferometer that are designed to split the 1310 nm channel from the 1490 and 1550 nm channels. The structure of the coupler includes 4 consecutive couplers linked with 3 different sets of arms with various phase delays. In principle, splitting of the 1310 nm channel from the 1490 and 1550 nm channels can be accomplished using a single-stage Mach-Zehnder interferometer. However, a 3-stage system was required to yield devices that are invariant with respect to processing non-uniformities. The couplers are polarization dependent in SOI. Controlling the stress of the cladding film makes the couplers polarization insensitive. We have used coupler matrix multiplication theory to arrive at optimal values for the physical phase delay in SOI that yields process invariant couplers: $\Delta\varphi_1 \sim 0.147$ µm, $\Delta\varphi_2 \sim 1.31$ µm, and $\Delta\varphi_3 \sim -0.147$ µm. The length of the couplers was chosen to be L_1 = 780 µm, L_2 = 300 µm, L_3 = 300 µm, and L_4 = 780 µm. One of the outputs of the Mach-Zehnder interferometer was coupled directly with a planar reflective grating. In general, the dispersion strength of a planar grating can be computed through the angle of incidence α and reflected angle α' (for derivation, see [9]):

$$\frac{\partial \alpha'}{\partial \lambda} = \frac{\sin\alpha + \sin\alpha'}{\lambda \cos\alpha'}\left[1 - \frac{\lambda}{n}\frac{\partial n}{\partial \lambda}\right] \qquad (1)$$

In our design, we chose α = 4.5° and α' = 3.5° to achieve sufficient angular dispersion strength. The grating order was selected to be 3. The construction of grating facets is described elsewhere [10, 11].

The monolithically integrated filter design was fabricated using standard CMOS-compatible process for fabrication of SOI structures. We have chosen the thickness of the core region to be 3 µm and the thickness of the insulating silica layer to be 0.375 µm. The grating facets were formed by etching through the entire thickness of the core region. In order to improve the planar grating reflectivity, a 100 nm layer of aluminum was deposited on the grating facets.

The fabricated filter was coupled to a single-mode fiber connected to a broad-band tunable, optical source. In order to properly ascertain spectral response of the filter, the output guides were coupled to a multi-mode fiber with a core diameter of 200-µm and numerical aperture of 0.4. A photodetector was used to measure the transmitted power as the optical sources were scanned. The performance of the multi-staged Mach-Zehnder interferometer is shown in Fig. 2(a). As designed, the coupler transmits a broad band around 1310 nm, allowing using an uncooled laser. The insertion loss of the coupler was measured to be 3.2 dB with a 1-dB bandwidth of 110 nm. It was independently verified that the fiber-chip-fiber loss for a straight waveguide was 2.9 dB with no anti-reflection coating. Consequently, the multi-staged Mach-Zehnder interferometer contributes about 0.3dB in Fig. 2(a).

In Fig. 2(b), a combined performance of the composite coupler and planar reflective grating is shown. The 1490 nm and 1550 nm channels have an insertion loss of about 5 dB, with planar reflective grating contributing about 1.8 dB to the overall insertion loss of the device. The adjacent channel isolation was measured to be better than 25 dB. The isolation between the 1310 nm channel and 1490 nm and 1550 nm channels was measured to be better than 45 dB.

The SOI filter had a footprint of only 1.5 × 0.18 cm^2 allowing potentially as many as many as 1000 devices to be manufactured on a single 8" in diameter wafer. Such remarkably low footprint, combined with large volume CMOS processing techniques can potentially result in low-cost PON transceivers based on SOIs.

III. Summary

We describe the design and fabrication of a monolithically-integrated silicon-on-insulator filter. The filter uses a combination of a cascaded Mach-Zehnder structure and a planar reflective grating to multiplex 1310 nm channel and demultiplex 1490 and 1550 nm channels for applications in passive optical networks.

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