Germanium-on-Silicon Mid-Infrared Photonic Integrated Circuits

A. Malik,[1,2] M. Muneeb,[1,2,3] S. Pathak, [1,2] Y. Shimura,[4,5] J. Van Campenhout, [4] R. Loo [4] and G. Roelkens[1,2,3]

[1] Photonics Research Group, Ghent University-imec, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium
[2] Center for Nano- and Biophotonics, Ghent University, 9000 Ghent, Belgium
[3] COBRA Research Institute, Eindhoven University of Technology, P.O. Box 513, Eindhoven 5600 MB,The Netherlands
[4] imec, Kapeldreef 75, Leuven, 3001, Belgium
[5] Instituut voor Kern- en Stralingsfysica, KU Leuven, 3001 Leuven, Belgium

Photonic integrated circuits based on the Germanium on Silicon platform are presented for operation in the 5 μm wavelength range. Waveguide losses in the range of 2.5 - 4 dB/cm for TE/TM polarization and Mach-Zehnder interferometers with an extinction of 20 dB for TE polarization are reported. Wavelength multiplexers based on Arrayed Waveguide Gratings are reported with an insertion loss and cross talk of -2.5/-3.1 dB and 20/16 dB for TE/TM polarized light while those based on Planar Concave Gratings are shown to have an insertion loss/cross talk of -4.9/-4.2 dB and 22/23 dB for TE/TM polarization.

Introduction

Photonic integrated circuits (PICs) have allowed the realization of various on-chip optical functionalities such as wavelength filters, (de)multiplexers, routers and switches. This has led to the development of compact and robust systems operating in the telecommunication wavelength range. Silicon on Insulator (SOI) is now the first choice material platform for this wavelength range because of (a) compatibility with the CMOS pilot lines which makes mass manufacturing possible and (b) higher index contrast which allows to make circuits with small footprint. For spectroscopic sensing applications, the wavelength regime which is of interest is the mid-infrared (3 - 12 μm). Most of the atmospheric gases and biological liquids have a strong absorption feature in this wavelength regime and therefore the development of PICs for longer wavelengths promises to provide compact hand held components which could be utilized to tap the full potential of this wavelength range. Silicon itself has a large transparency window from 1.2 μm to 8 μm however the underlying oxide starts absorbing beyond 4 μm [1]. Various alternative waveguide platforms have been proposed in recent literature such as free standing Si[2], Silicon on Sapphire[3], Silicon on Silicon Nitride[4] and Germanium on Silicon[5]. The key requirements for a waveguide platform are (a) transparency in the wide mid-IR, (b) straightforward fabrication scheme and (c) CMOS compatibility which will allow mass manufacturing.

Free standing Si has a very wide transparency window but suffers from the fact that the waveguide structures are fragile and prone to collapsing. Silicon-on-Sapphire has a transparency limited to 5.5 μm because of the sapphire absorption and Silicon-on-Silicon Nitride has a complicated fabrication scheme which requires wafer bonding. Germanium-on-Silicon fits all the above mentioned requirements and thus seems the ideal candidate for the mid-IR.

In the past decade, advancements in Quantum cascade lasers (QCLs) and Interband cascade lasers (ICLs) have enabled efficient on chip mid-IR light generation[6]. The integration of these light sources with a passive PIC can help in the realization of interesting functionalities. Two possible applications based on this integration are described in Fig 1. In a first case, a broad band fabry-perot QCL is integrated with a wavelength selective feedback circuit present on the passive PIC. This can enable the realization of a compact and hand held mid-IR light source and can replace existing bulky devices. In second case, an array of DFB lasers can be integrated with a wavelength multiplexer present on the PIC. This arrangement promises to allow efficient on -chip beam combining which has been realized using free space optics till now.

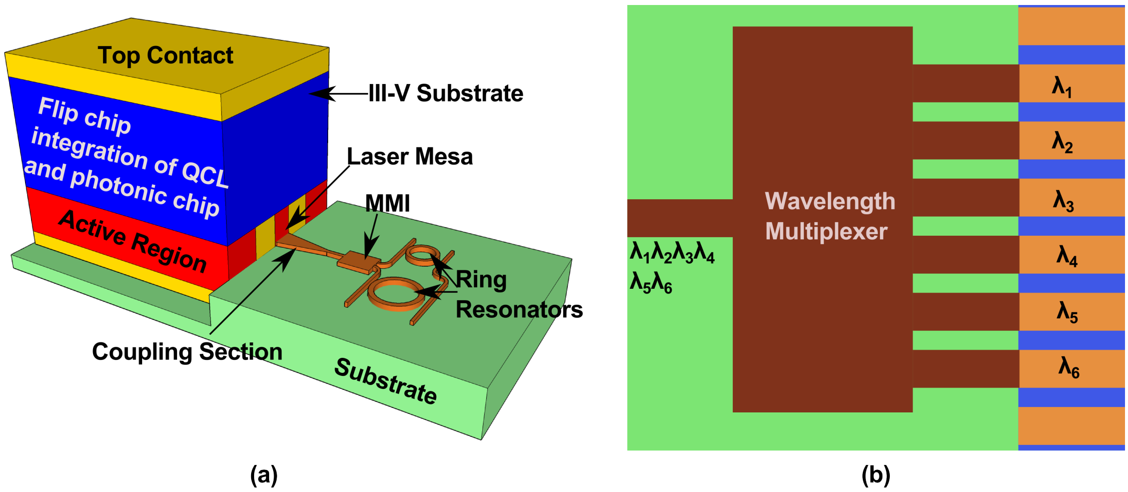

Figure 1: Schematic diagram of (a) a broadband QCL integrated with a photonic chip via flip chip integration and (b) an array of DFB QCL lasers integrated with a wavelength multiplexer.

Waveguide Loss

Fully etched waveguides (etching through the 2 μm thick Ge waveguide layer)of width 2.2 μm and lengths 0.5 cm, 1 cm, 2 cm and 3 cm were characterized for transverse electric (TE) and transverse magnetic (TM) polarizations[7]. The fabrication details of these waveguides and the measurement setup required to characterize these waveguides is described in [7]. Fig. 2 (a) and (b) respectively show the cutback measurements at 5.3 μm and the waveguide losses for the 5.15 - 5.45 μm wavelength range are presented in Fig. 2 (c) for both polarizations.

Mach Zehnder Interferometers

1×1 and 1×2 Mach Zehnder interferometers (MZIs) were designed using 1×2 and 2×2 Multimode interferometers (MMIs) with a delay length of 260 μm for TE polarized

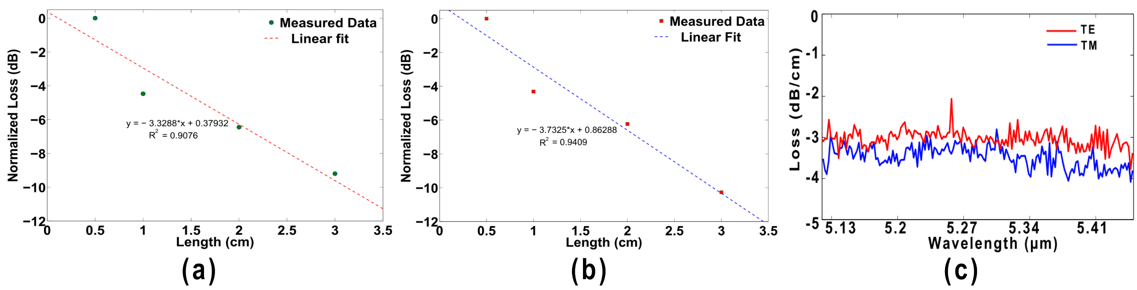

Figure 2: Cutback measurements at 5.3 μm for (a) TE polarized light, (b) TM polarized light and (c) loss measurements in the 5.1 - 5.45 μm wavelength range for TE and TM polarizations.

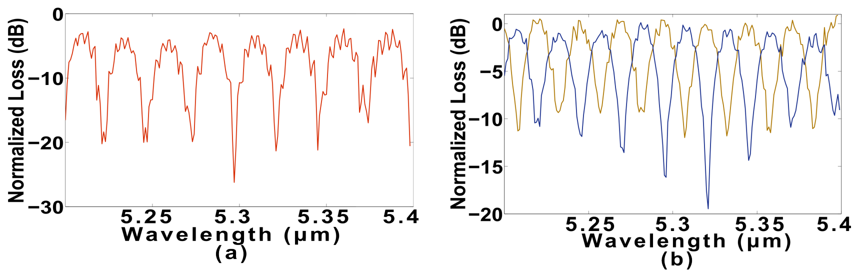

Figure 3: Normalized spectrum of (a) 1×1 MZI and (b) 1×2 MZI.

light[8]. This resulted in a free spectral range (FSR) of 25 nm and an extinction of 23 dB for a 1×1 MZI at 5.3 μm and 20 dB for a 1×2 MZI at 5.32 μm as seen in Fig. 3 (a) and (b) respectively. An array of such MZIs can be used as wavelength multiplexer to enable mid-ir beam combining.

Arrayed Waveguide Gratings

A 5×200 GHz arrayed waveguide grating (AWG) was designed and found to have an insertion loss of -2.5/-3.1 dB while the cross talk was found to be 20/16 dB for TE/TM polarization[7]. Normalized spectra for TE and TM polarizations are shown in Fig 4 (a) and (b) respectively. Since the AWG has a lower insertion loss and cross talk, it can be deployed both to separate broadband light in different channels and to combine light from individual DFB lasers in a single beam.

Planar Concave Gratings

A six channel planar concave grating (PCG) having DBR gratings with 25 nm channel spacing was designed and found to have an insertion loss of -4.9/-4.2 dB and cross talk of 22/23 dB for TE/TM polarizations[9]. Normalized spectra for TE and TM polarizations are shown in Fig 5 (a) and (b) respectively. The insertion loss of the PCG is higher than the AWG however this is mainly due to the fact that because of the limits of i-line contact lithography, the minimum feature is 1 μm. This results is a third order DBR with 66% reflection. With the access to standard CMOS tools, first order DBRs can be fabricated which will reduce the insertion loss enabling the use of this PCG as wavelength (de)multiplexer.

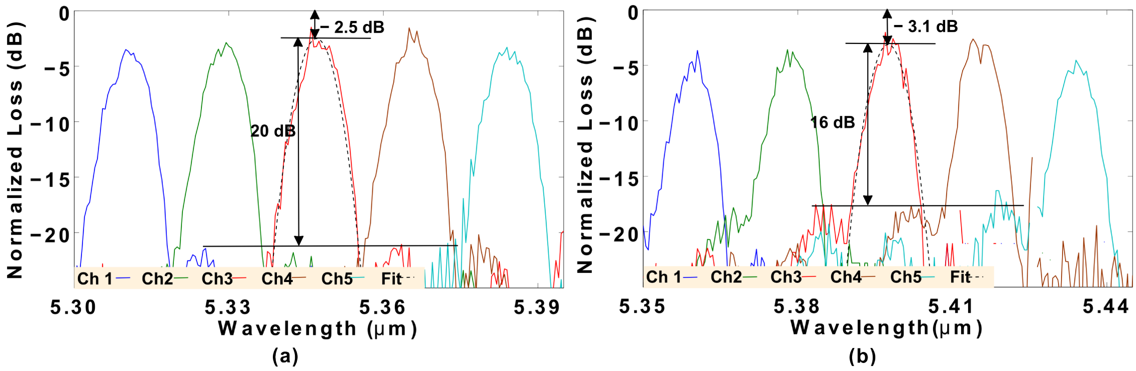

Figure 4: Normalized spectrum for a 5×200 GHz AWG for (a) TE polarized light and (b) TM polarized light.

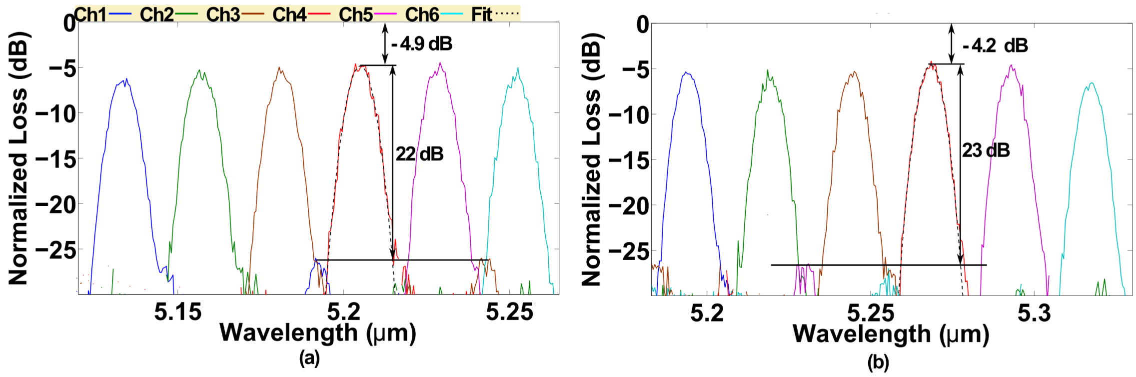

Figure 5: Normalized spectrum for a 6 channel PCG with 25 nm channel spacing for (a) TE polarized light and (b) TM polarized light.

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