# Ten gigabit per second optical transmissions at 1.98 µm in centimetre-long SiGe waveguides

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Error-free transmission of 10 Gbit/s non-return to zero optical signals along 2.5 cm long silicon germanium waveguides at a wavelength of 1.98 µm is demonstrated. Bit error rate measurements confirm the absence of penalty during the transmission through a subwavelength of 1.3 and 2.2 µm wide waveguides.

*Introduction:* Silicon photonics currently attracts much attention as an emerging technology for on-chip communication and all-optical processing. This interest is even more pronounced with the recent shift towards mid-infrared wavelengths. Indeed, in order to face the continuous and inexorable increase of the data traffic and to avoid the so-called 'capacity crunch', attention now focuses on non-conventional spectral regions, including the 2 µm spectral band that can benefit from the emergence of thulium-doped fibre amplifier (TDFA) [1]. This trend has stimulated studies of dedicated photonic components such as InP-based modulators [2], arrayed waveguide gratings or low-loss hollow core bandgap photonic fibres for transmission over hundreds of metres [3, 4].

In this Letter, we investigate the performance of silicon germanium (SiGe) waveguides. Such components have been thoroughly studied in the C-band [5] where their non-linear properties have been beneficial for ultrafast optical processing [6]. However, such waveguides are expected to reach even better performance at mid-IR wavelengths. Even though they have been used to convert a signal from mid-IR to C-band [7], no high bit-rate transmission has been reported so far. Here, we demonstrate, for the first time, an error-free transmission of a 10 Gbit/s on–off keying signal at 1.98 µm in 2.5 cm long SiGe waveguides. Two waveguides having different widths are compared.

*Waveguide design and fabrication:* We have designed and fabricated two optical waveguides sketched in Fig. 1*a* and made of $Si_{1-x}Ge_x$ grown on a Si substrate and encapsulated in Si. Both structures have a 1.4 µm height and a length of 2.5 cm but their widths differ. We compare the performances of a subwavelength of 1.3 µm wide device and a 2.2 µm wide waveguide. Optical losses in the 2 µm spectral region are expected to be as low as 2 dB/cm, so that propagation through 2.5 cm is fully realistic. The high contrast of optical indexes between SiGe and Si (3.54 and 3.45, respectively, at a wavelength of 1.98 µm [8]) enables excellent confinement of the light within the waveguides (see Figs. 1*b* and *c*). At the wavelength under study, the 1.3 µm waveguide is bimodal and can handle one TE mode and one TM mode, whereas the 2.2 µm wide waveguide can guide two TE and two TM modes. The TE and TM fundamental modes have almost identical indices. In order to facilitate butt-coupling injection/collection of light to/from the waveguide, 5 µm wide and 500 µm long input and output tapers have been included in the photonic components. The external facets are cleaved at normal incidence.

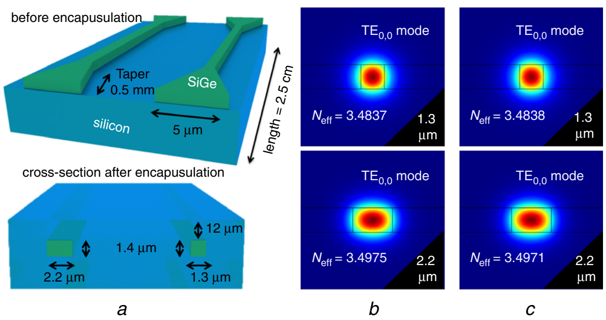



**Fig. 1** *Design and fields for 1.3 µm wide (at top) and 2.2 µm wide (at bottom) waveguides*

*a* Sketches of studied waveguides before encapsulation
*b* Field of TE fundamental mode for two waveguides
*c* Field of TM fundamental mode for two waveguides

The fabrication process consists of several epi-layers of $Si_{1-x}Ge_x$ grown on an Si substrate. First, a 1.4 µm thick SiGe layer with 20% germanium concentration ($x = 0.2$) was grown by reduced pressure chemical vapour deposition (RP-CVD) to control precisely the germanium concentration and thus preserve uniformity. Then, standard photolithography and deep reactive ion etching were used to form the strips. Finally, the waveguides were encapsulated with a 12 µm Si cladding layer epitaxially grown with the same RP-CVD technique.

*Experimental set-up:* In order to demonstrate the suitability of our SiGe components for high-speed optical transmission around 2.0 µm, we have implemented the set-up presented in Fig. 2. The transmitter is based on a laser diode (CW – continuous wave) centred at a wavelength of 1.98 µm and intensity modulated by means of a lithium-niobate modulator. The transmitted signal is a $2^{31} - 1$ pseudo-random bit sequence at 10 Gbit/s encoded by a non-return to zero on–off keying modulation format. A polarisation controller is inserted after the intensity modulator so as to mitigate the polarisation sensitivity of SiGe waveguides. An optical isolator is also included to protect the active devices from the spurious Fresnel back-reflections that may arise at the component facet due to the large optical index difference between air and Si. Light is injected into the waveguide through butt-coupling taking advantage of optical lensed fibres.

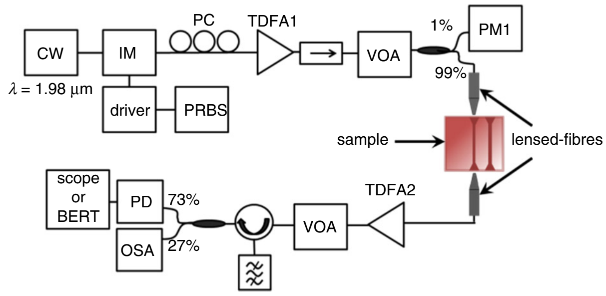


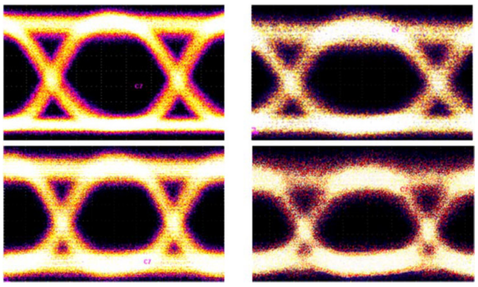

**Fig. 2** *Experimental set-up for 10 Gbit/s transmissions at 1.98 µm. CW: continuous wave; IM: intensity modulator; PC: polarisation controller; TDFA: thulium-doped fibre amplifier; VOA: variable optical attenuator; PM: power meter; PRBS: pseudo-random bit sequence; OSA: optical spectrum analyser; PD: photodiode*

Two variable optical attenuators are inserted into the set-up: the first one is used to control the power injected into the device and thus adjust the optical signal-to-noise ratio (OSNR) at the receiver, whereas the second one preserves a constant power on the photodiode (PD). A power meter and an optical spectrum analyser (OSA) measure the power before and after transmission, respectively. The OSA is also used to evaluate the OSNR of the received signal. The PD can be connected either to a high-speed sampling oscilloscope or to a bit error rate (BER) tester in such a way to monitor the output eye diagrams or perform the BER measurements, respectively. An optical bandpass filter is inserted into the set-up in order to limit the accumulation of amplified spontaneous noise emission generated from the two TDFAs.

*Experimental results at 2 µm:* We have successively tested the subwavelength and the 2.2 µm wide waveguides for optical data transmissions. Total fibre-to-fibre losses close to 33 and 30 dB have been measured, respectively, for polarised CW light at 1.98 µm. Note that our goal here was not to optimise the optical coupling (the tapers that are present are identical and have not been optimised for each waveguide width individually). We have noted experimentally that given its design accepting both TE and TM modes with similar efficiency, the subwavelength waveguide was only marginally polarisation dependant.

The eye diagrams shown in Fig. 3 offer us an initial overview of the quality of the 10 Gbit/s transmissions. The eye diagrams after propagation are well open both for the subwavelength and for the 2.2 µm wide waveguides and do not exhibit significant degradations compared to the back-to-back measurements.

To further evaluate the quality of the high-speed optical transmissions at 1.98 µm, BER measurements have been carried out for the two devices. Error-free transmissions (BER $\leq 10^{-12}$) at 1.98 µm wavelength have been achieved through both 2.5 cm long SiGe waveguides of two different widths. Quantitative measurements of the influence of the OSNR on the output BER are summarised in Fig. 4. For each structure, BER measurements after transmission through the waveguide are compared with the result obtained in back-to-back configuration (to this aim, a variable optical attenuator with equivalent losses to the device is used replacing the structure and the two lensed fibres). As can be seen, results are very similar and propagation through the photonic component does not induce any power penalty. Furthermore, the bimodal or multimodal properties of the waveguides do not seem to impact the transmission quality. Given the input power injected into the waveguide (peak power of 150 mW is typically coupled to the waveguides), the various non-linear effects that may exist in Si or SiGe materials and that are used in the context of optical processing do not impair the propagation. To support this argument, we have checked the output spectrum and found it rather identical to the input one.



*a* *b*

**Fig. 3** *Eye diagrams for 1.3 μm wide SiGe waveguide (top) and 2.2 μm wide SiGe waveguide (bottom)*

*a* Back-to-back configuration
*b* After transmission through waveguides

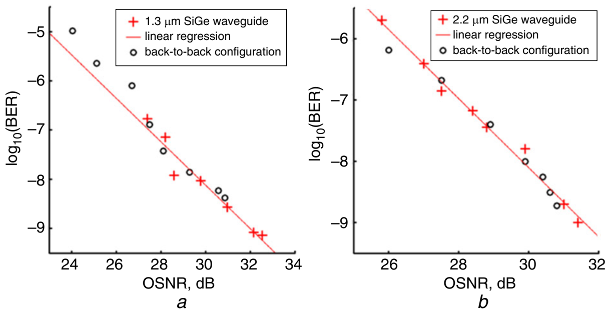



**Fig. 4** *BER as function of OSNR for 2.5 cm long SiGe waveguides. Black circles are associated with the back-to-back configuration while red crosses indicate BER measurements at output of waveguides. Red line corresponds to associated linear regression*

*a* Graph for 1.3 μm wide SiGe waveguide
*b* Graph for 2.2 μm wide SiGe waveguide

*Conclusion:* We have demonstrated error-free transmission of 10 Gbit/s optical signals in SiGe 2.5 cm long waveguides at the wavelength of 1.98 μm. No significant penalty has been recorded on the BER measurements after transmission into a subwavelength waveguide and through waveguide having a width of 2.2 μm. These results pave the way for the use of SiGe-based components for high-repetition rate transmissions combined with simultaneous non-linear processing in the near-infrared region.

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One or more of the Figures in this Letter are available in colour online.

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