# Integrated electro-optical modulator operating in the long-wave infrared spectral range

(Student paper)

**Thi Hao Nhi Nguyen[1], Natnicha Koompai[1], Miguel Montesinos-Ballester[1], Lucas Deniel[1] , Jacopo Frigerio[2], Andrea Ballabio[2], Virginia Falcone[2], Xavier Le Roux[1], Carlos Alonso-Ramos[1], Laurent Vivien[1], Adel Bousseksou[1], Giovanni Isella[2], and Delphine Marris-Morini[1]**

*1 Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, 91120 Palaiseau, France*
*2 L-NESS, Dipartimento di Fisica, Politecnico di Milano, Polo di Como, Via Anzani 42, 22100 Como, Italy*
*e-mail: thi-hao-nhi.nguyen@universite-paris-saclay.fr*

**Abstract:** Free carrier plasma dispersion effect has been exploited to obtain an integrated electro-optical modulator operating in a broad spectral range of the mid-infrared regime. This modulator is based on a Schottky diode used to modulate free carrier concentration in a graded Silicon Germanium (SiGe) optical waveguide and to obtain modulation of the optical transmission. In the first experimental demonstration, operation was obtained from 6.4 to 10.7 µm wavelength with a single device. The dynamic characterization was performed up to 225 MHz. The work now focuses on the design of electrical access and RF electrodes to achieve high speed operation. Interestingly electro-optical bandwidth of a few tens of GHz is expected. © 2022
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## INTRODUCTION

Mid-infrared (mid-IR) spectroscopy is of a great importance to detect the traces related to environmental and toxic vapors. The on-chip integration of spectroscopic system is promising for the development of sensors with high efficiency and compactness. Due to their vibrational and rotational resonances, many molecules can be detected in the mid-IR spectral range, especially for the wavelengths from 5 µm to 11 µm [1-3]. Integrated electro-optical modulator (EOM) operating in this wavelength range is interesting for many applications, such as sensitivity enhancement via on-chip synchronous detection. Recently, we have demonstrated the first integrated modulator based on a silicon germanium (SiGe) graded-index platform operating from 6.4 to 10.7 µm wavelength [4]. This modulator exploits free carrier concentration variations in a Schottky diode to obtain absorption coefficient variations. In this work, we evaluate the possibility to improve the device performance to achieve high speed operation.

## RESULTS

### a. Experimental results

The schematic view of the integrated modulator is depicted in Fig. 1a. It relies on a graded SiGe waveguide in which the concentration of Germanium linearly increases from 0 to 100%, which is responsible for a linear increase of the refractive index in the waveguide. The 6 µm-thick graded layer is grown on a highly n-doped Silicon substrate with doping concentration of 2 x $10^{19}$ $cm^{-3}$, which allows for electrical access from the backside of the sample. The graded epi layer is non-intentionally doped, with a residual n-doped concentration estimated to be in the order of $10^{15}$-$10^{16}$ $cm^{-3}$. The waveguide width and etching depth are 5.5 µm and 6.8 µm, respectively. The electric field profile of the TE mode at the wavelength of 8.5 µm is shown in Fig. 1b, showing a light confinement at the top of the waveguide. Electrical contacts are deposited on the backside of the sample and on the top of the waveguide, forming a vertical Schottky diode at the top of the waveguide. When tuning the voltage applied to the device, the variation of free carriers in depletion or injection regimes is thus responsible for variation of the absorption coefficient of the guided mode, and for modulation of the optical transmission. Fig. 1c shows a SEM image of the fabricated sample with 2.6 mm-long modulators.

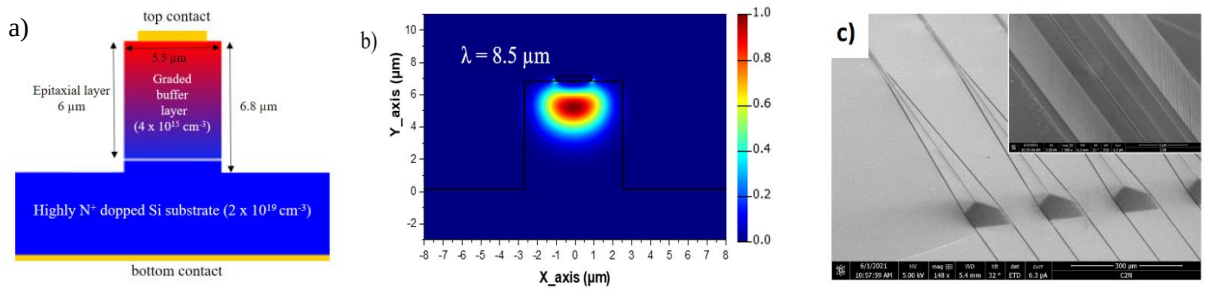


Fig. 1. (a) Schematic view of the modulator. (b) Electric field profile of the TE mode at 8.5 µm wavelength. (c) SEM picture of the fabricated device. The optical taper used to enlarge the waveguide and the top contact layer, to apply the electrical probe can be seen.

First, the modulation has been characterized in terms of modulation efficiency. In the injection regime, the concentration of free charge carriers in the optical waveguide increases by applying a direct voltage on the diode. Thus, the relative optical transmission gradually decreases when the current increases. The highest extinction ratio obtained in this configuration is 1.3 dB at the wavelength of 10.7 µm (Fig. 2a). In the depletion regime, free carriers are extracted out of the depletion region, thus the relative optical transmission increases when the reverse bias voltage increases (Fig. 2b).

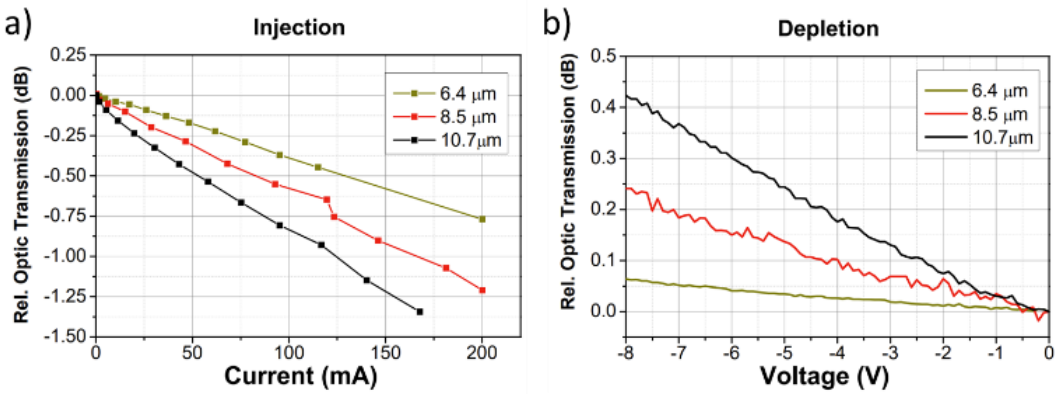


Fig. 2. Electro-optical modulation in TE polarization (a) in the injection regime and (b) in the depletion regime.

Dynamic characterization has also been performed. To this end, the light coming out from the output of the device is sent to a fast mid-IR detector operating up to 600 MHz. An RF electrical signal is applied to the modulator, and an electrical spectrum analyzer is used to measure the photodetected signal as a function of the RF frequency that is applied. Fig. 3 shows the photodetected signal as a function of the RF frequency in both injection and depletion schemes. As observed in injection regime, the signal linearly decreases when the electrical frequency is larger than 50 MHz, which is attributed to the effect of free carrier recombination lifetime. In depletion regime, the modulated signal is almost flat up to frequency of 225 MHz, while measurement at higher frequency is limited by the noise.

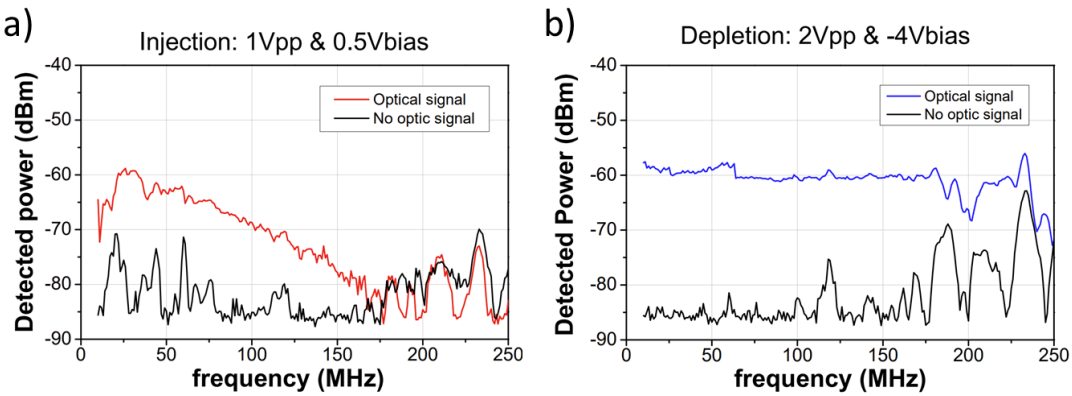


Fig. 3. Amplitude of the photodetected signal as a function of the RF frequency in (a) carrier injection regime and (b) carrier depletion regime.

**b. Design for high-speed operation**

While the achieved performances are already compatible with applications such as on-chip synchronous detection, it is highly interesting to investigate the possibility to reach higher frequency operation. To this end, the focus will be given on the depletion regime, where few tens of GHz of electro-optical bandwidths are expected. A careful design of the electrical access and the RF electrodes is then needed, in order to: (i) ensure that the equivalent RC product is compatible with high-speed operation; (ii) achieve impedance matching with the equipment used for the electro-optical characterization (50 ohms) to avoid high RF signal reflection; (iii) reduce the speed difference between electrical and optical signals propagating along the modulator.

The use of grounded coplanar waveguide (CPWG) electrodes is investigated to that end. A distributed model considering both light and electrical signal propagation is considered and used to evaluate the electrical S parameters and the 3 dB electro-optical bandwidth. The equivalent electrical circuit of the Schottky diode is implemented, both in terms of equivalent capacitance (obtained from simple electrical modelling) and access resistance (based on experimental results). Finally, the parameters of the electrodes, such as the width of the signal line path and the distance between the signal and the ground are optimized by numerical calculations. Interestingly, it will be shown that electro-optical bandwidth of a few tens of GHz can be expected.

**CONCLUSION**

This work focuses on an integrated electro-optical modulator based on a Schottky diode embedded in a graded SiGe optical waveguide. This modulator can operate in a wide wavelength range of the mid-IR spectrum (6.4 - 10.7 µm). While the first experimental results were limited to modulating frequencies below 250 MHz, the design of the electrical contacts and RF electrodes has been carried out to optimize the electro-optical bandwidth. Interestingly, by using grounded coplanar waveguide electrodes, electro-optical bandwidth of a few tens of GHz are expected.

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