Mid-infrared Fourier-transform spectrometer based on suspended silicon metamaterial waveguides

(Student paper)

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Integrated mid-infrared micro-spectrometers hold great potential for environmental monitoring and aerospace applications. The use of silicon-on-insulator in the mid-infrared is limited by the absorption of the buried oxide layer beyond 4 µm wavelength. We overcome this limitation by using metamaterial-cladded suspended silicon waveguides to implement a Fourier-transform spectrometer operating near 5.5 µm wavelength.
Keywords: *Fourier-transform spectroscopy, mid-infrared, metamaterial, silicon photonics*

INTRODUCTION

The mid-infrared (mid-IR), spanning wavelengths from 2 to 20 µm, is a crucial wavelength range for spectroscopic applications because it comprises the absorption fingerprints of many chemical and biological compounds. Mid-IR optical spectrometers are employed in a wide variety of applications, including food safety, medical diagnostics, indoor air quality monitoring, astronomy, and resource exploitation [1]. Integrated spectrometers that can provide high sensitivity and real-time monitoring within ultra-compact and low-cost chips are highly sought after in mid-IR applications. Spatial heterodyne Fourier-transform spectrometers (SHFTS) have significant benefits in terms of optical throughput, resolution, and resilience against manufacturing imperfections [2]. The compatibility of SHFTS with passive calibration techniques enables software correction of amplitude and phase errors, as well as machine-learning algorithms for enhanced resilience against environmental instabilities [3].

Silicon photonics holds great potential for the implementation of compact and low-cost integrated spectrometers in the mid-IR, especially SHFTS [4]. Mid-IR SHFTS based on SiGe technology have recently been reported to reach 8.5 µm wavelength with a resolution of 15 cm^{-1} [5]. However, demonstrations of SHFT spectrometers based on silicon-on-insulator (SOI) technology are restricted to 3.75 µm wavelength (2 cm^{-1} resolution) due to the strong absorption of the buried oxide (BOX) layer for wavelengths above 4 µm [6]. Since their first demonstration in silicon photonics [7,8], subwavelength-grating (SWG) metamaterials [9] have been used as a powerful tool for refractive index engineering, overcoming performance limitations of conventional silicon photonic devices. Suspended silicon membrane waveguides with SWG cladding have been recognized as a potential solution to exploit the full silicon transparency window (1.1-8 µm wavelength range) [10]. This type of waveguide allows for the selective removal of the BOX layer underneath the waveguide core while benefiting from the high index contrast of silicon waveguides.

In this work, we demonstrate a SHFTS implemented with suspended silicon waveguides based on SWG metamaterial (see Fig. 1), effectively circumventing operational wavelength limits induced by BOX absorption. We demonstrate SHFTS operation near a wavelength of 5.5 µm, with a spectral resolution of approximately 13 cm^{-1}.

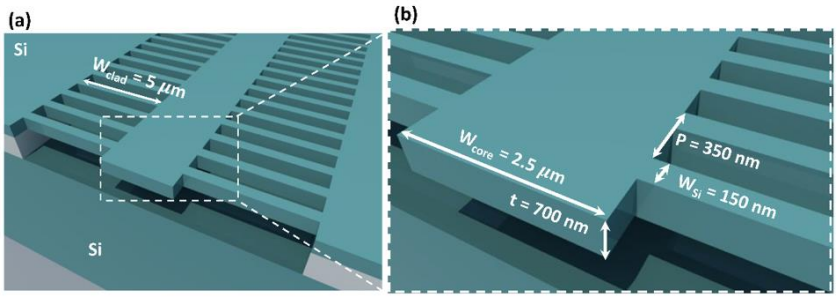

Fig. 1: (a) Schematic of a suspended silicon waveguide with metamaterial lateral cladding; (b) detailed view showing the main geometrical parameters.

RESULTS

We implemented the SHFTS as an array of 19 Mach-Zehnder interferometers (MZIs) with different optical path lengths ranging from 20 µm to ΔL_{Max} = 200 µm. These parameters yield a theoretical resolution of 13 cm^{-1}, and a free spectral range (FSR) of 120 cm^{-1}. Figure 1 shows the schematic of the suspended silicon waveguide with metamaterial cladding used for the implementation of the MZIs. The metamaterial cladding offers mechanical stability and necessary effective lateral index contrast to confine the optical mode, while still requiring manufacture with a single Si etch step. The suspended SWG waveguides were implemented on the SOI platform with a silicon thickness of 700 nm, and a buried oxide layer thickness of 3 µm. The waveguide core width is 2.5 µm, and the cladding width is 5 µm. The lateral cladding grating has a period of 350 nm. To allow the penetration of hydrofluoric (HF) acid vapor for substrate removal, we select a gap length of 200 nm. Figure 2a presents the optical image of the fabricated spectrometer with a total footprint of 18 mm x 7.1 mm. Scanning electron microscopy (SEM) images of the suspended SWG waveguide and a Y-junction splitter are shown in Fig. 2c and 2b, respectively.

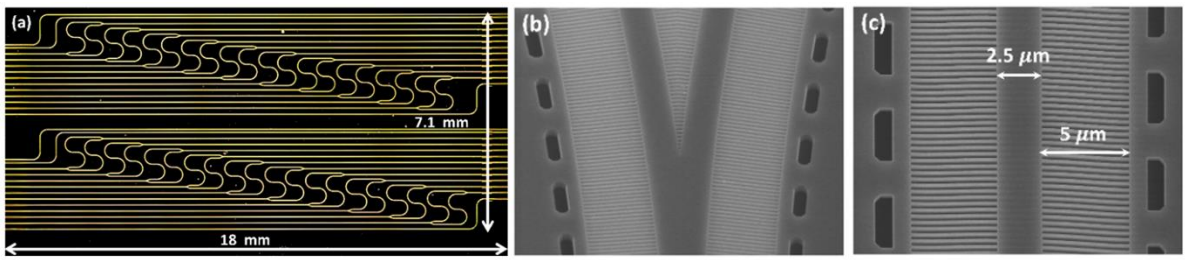

Fig. 2: (a) Optical image of the fabricated SHFTS. (b) SEM images of Y-juction splitter, and (c) metamaterial-cladded suspended waveguide.

Light from a tunable quantum cascade laser was injected and extracted from the chip using aspheric ZnSe lenses to measure the device's performance. A mercury-cadmium-tellurite (MCT) photodetector was used to measure the output signal. To determine the propagation losses of the suspended waveguides, we used the cut-back method by sampling the optical transmission of four waveguides with different lengths ranging from 1.4 cm to 2.58 cm. Our suspended waveguides show propagation losses of 1-2 dB/cm between 5.2 and 5.7 µm wavelengths. We applied the pseudo-inverse matrix approach to calibrate the SHFT spectrometer and retrieve the input spectrum [2]. The pseudo-inverse retrieval approach is beneficial for correcting amplitude and phase errors caused by manufacturing imperfections. The input spectrum B is retrieved by the product between the output spectrum I and the calibration matrix T, which comprises the transmittance spectra of 19 MZIs. Figure 3a shows the measured calibration matrix T. For signal retrieval, we chose a bandwidth of 100 cm^{-1}, which corresponds to the theoretical calculation of the FSR. Figures 3b-3d present the retrieved spectra for monochromatic and doublets signals for wavelengths near 5.44 µm, 5.5 µm, and 5.6 µm, respectively. Correct doublet retrieval demonstrates a spectral resolution of approximately 13 cm^{-1}.

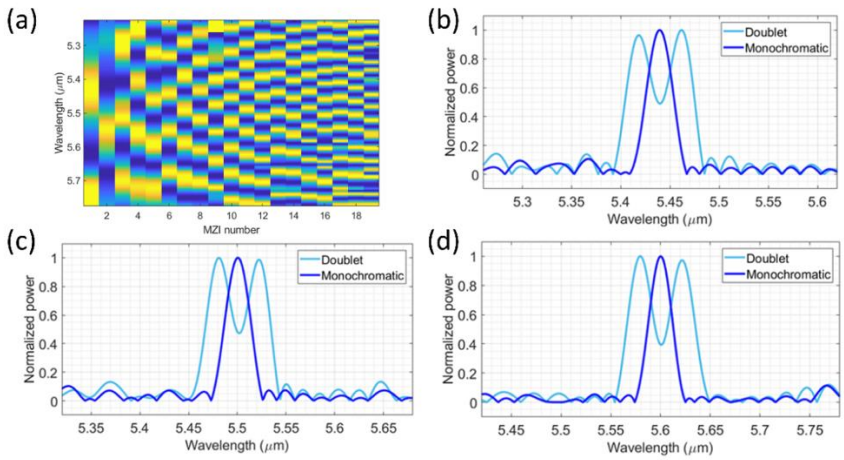

Fig. 3: (a) Calibration matrix of a SHFT with 19 MZIs. Retrieved spectrum of monochromatic and doublet inputs with peak-to-peak spacing of 13 cm^{-1} in the bandwidth of 100 cm^{-1}, for wavelengths around (a) 5.44 µm, (b) 5.5 µm, and (c) 5.6 µm.

DISCUSSION

In conclusion, we presented an integrated mid-IR SHFTS chip implemented with suspended silicon waveguides with metamaterial grating cladding. This device overcomes the major limitation of the SOI technology in the mid-IR by circumventing the absorption of the silica BOX for wavelengths above 4 µm. Fabricated waveguides present propagation loss of ~2 dB/cm near 5.5 µm wavelength. The SHFTS chip yields a measured resolution of 13 cm^{-1} and a bandwidth of 100 cm^{-1}. To the best of our knowledge, this is the longest wavelength reported for an integrated silicon SHFT spectrometer. These findings pave the way for the development of integrated spectrometers with high throughput and resistance to manufacturing imperfections while taking advantage of the whole silicon transparency range.

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