Novel high contrast grating hollow core waveguides for enhanced gas spectroscopy

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Abstract. The article presents an innovative approach to confining waves in planar high contrast grating hollow core waveguides, design achieves a surface that reflects waves effectively while maintaining a structure that allows for high transmission. The unique side-open waveguide system also allows for gas flow through the sidewalls, making it suitable for gas spectroscopic techniques. The HCW design is specifically tailored for methane gas sensing at a wavelength of 3.27 µm. Numerical analysis shows that the transmittance can reach up to -0.41 dB. These findings demonstrate the potential of high-transmitting hollow-core waveguides for gas sensing, highlighting the effectiveness and cost-efficiency of chip-scale photonic integration.

1 Introduction

Efficient light and matter interaction is essential for improving sensitivity and selectivity in gas sensing applications. Hollow-core optical waveguides/fibers offer a compact solution that allows for increased interaction lengths between light and gas molecules. Particularly, hollow-core waveguides (HCWs) are proficient in transmitting infrared (IR) to terahertz (THz) radiation, enabling effective high-power laser delivery using materials with low absorption properties [1]. HCWs feature a central air core enveloped by a highly reflective inner wall, enabling the transmission of light across a broad spectral range with minimal attenuation. Integrated on-chip platforms utilizing HCWs offer further advantages, allowing gases or fluids to be introduced into the waveguide from side openings rather than solely from the ends. In contrast, traditional solid-core waveguides encounter challenges in identifying materials with suitable optical, thermal, and mechanical characteristics [2]. In comparison to hollow core fibers (HCFs), integrated hollow waveguides platforms provide additional benefits such as the fabrication of single etch reflecting surfaces and the concurrent injection of laser and gas [3,4].

This paper introduces a numerical analysis of the design for an ultra-high reflecting surface and a high-contrast grating (HCG) assisted HCW, specifically for gas sensing applications, with a focus on detecting Methane (CH_4) at 3.27 µm. The study commenced with a unit cell analysis to evaluate the performance of high-contrast materials by calculating reflectance. The HCW, designed for the first time using the beam propagation method, demonstrates remarkably low loss values, with a maximum of -0.410 dB in propagation systems.

2 Design and Methodology

Achieving lateral confinement in the y-direction is accomplished through the utilization of various high contrast sub wavelength grating (HCG) designs for the core and cladding regions, ensuring that the effective refractive index of the core surpasses that of the cladding. Figure 1 illustrates the schematic representation of the proposed optical setup to be utilized in the study. A modulated micro laser beam is butt coupled onto the HCG-HCW. The distance between the chip platforms is denoted as 'd', with a total length of 'L'. Within the HCW, the incident light indeed adopts the overall light pattern propagating in the waveguide is composed of plane waves.

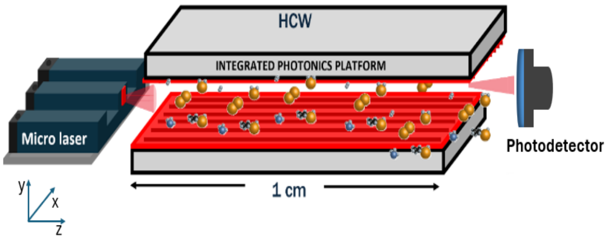

Fig. 1. The schematic of the gas detection scheme utilizing the HCW.

These individual plane waves can be reflected from the top and bottom facets during propagation, facilitating interaction with gas molecules. Subsequently, the light, integrated with gas molecules, is directed towards the photodetector. For characterization purposes, a camera and photodetector are positioned downstream of the HCW

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to capture and analyze the transmitted light. The entire setup is housed within a gas chamber for gas sensing applications. To achieve a high level of confinement, we utilize HCG elements, known for their impressive performance in reflecting light incident at a perpendicular angle to the surface. To comprehend how the grating structure confines light, we analyze a unit cell depicted as in Figure 2 (a), employing Rigorous Coupled Wave Analysis (RCWA) on the silicon-on-silicon dioxide (Si/SiO2) platform [5,6]. During this analysis, we calculate the complex reflection coefficient 'r' of the HCG using RCWA, maintaining an index resolution of 0.001 and employing periodic boundary conditions. The width of the grating element (C) and the period are optimized for the wavelength of interest, i.e., in at wavelength 3.27 µm in Figure 2(b), achieves a 98% reflecting surface.

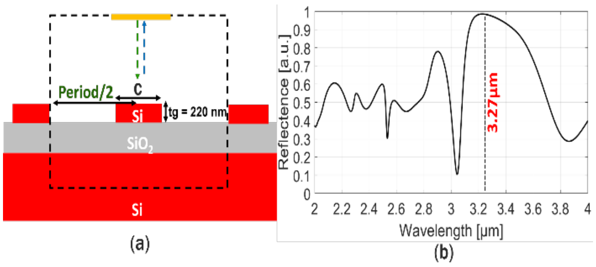

Fig. 2: (a) Unit cell configurations in 2D simulations of structures exhibiting periodicity along a single axis. (b) reflectance spectra of the unit cell configurations.

Consider a scenario where the electric field is incident vertically, i.e. purely quasi-TE mode, within the HCW. For constructive interference to occur, the phase difference between the reflected modes at the air/Silicon interface and after traversing the SiO2 layer must equate to $\delta m = 2m\pi$, where m is an integer representing the order of interference (m = 1, 2, 3, ...).

3 Results and Discussion

The silicon grating structures are aligned parallel to the direction in which light propagates. These structures are positioned on top of a silicon dioxide substrate, which is then placed on a silicon box wafer. The thickness of the grating elements remains constant at 220 nm. The design consists of two main parts: the uniform period structure section and the chirped grating section. In the uniform period structure section, the width and period of the grating are optimized. As we move into the chirped section, the width of the grating gradually changes from 'W_i' to 'W_f', along with a corresponding period adjustment. The number of elements in this chirped section is optimized to induce a change in the effective refractive index.

The HCW, optimized for 3.27 µm, is designed with parameters specifically tailored to accommodate its longer wavelength. These parameters include a uniform period of 2.6 µm, a core width of 1.55 µm. The HCW dimensions feature a diameter (d) of 12 µm. During simulation, a Gaussian beam is employed to excite the HCG-HCW. Figure 3 (a) illustrates the loss in dB as a function of wavelength for the HCW design.

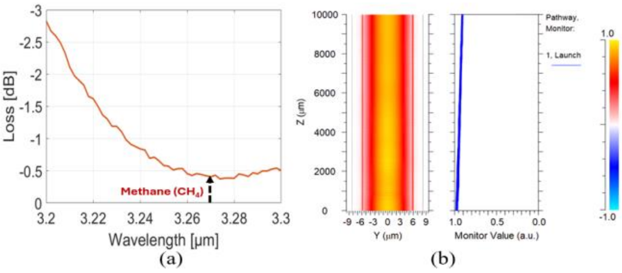

Fig. 3: Depicts HCW over a 1 cm length of the waveguide, (a) loss spectrum of the plotted against wavelength and (b) the electric field profile of the HCW.

Figure 3 (b) illustrates the propagation of the electric field in HCW, accompanied by monitors positioned throughout the air core, serving as path monitors. The demonstration of lateral confinement in planar HCG-HCW represents a pioneering strategy in waveguide engineering, utilizing surface phase manipulation. By maintaining a fixed thickness for the HCG while adjusting the periods and grating bar widths, diverse reflection phases can be generated while ensuring high reflectance. This approach facilitates high light-matter interaction, making it well-suited for compact gas sensors.

The authors gratefully acknowledge financial support by European Union’s Horizon 2020 IA project “Photonic Accurate and Portable Sensor Systems Exploiting Photoacoustic and Photo-Thermal Based Spectroscopy for Real-Time Outdoor Air Pollution Monitoring (PASSEPARTOUT, grant No. 101016956) and by Science Foundation Ireland project METASPECS SFI- 21/FFP-A/10002.

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