Investigation on optical integration between LED Mid-IR light sources and Si-based waveguides for sensing applications

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Abstract. Research on mid-IR silicon-based waveguides has recently received strong interest. Particularly, this paper focuses on one of the critical issues in micron-scale photonic integrated circuits, which is to efficiently couple a mid-IR LED (light emitting diode) light source to an external micron-scale waveguide. The optical coupling scheme is crucial for the exploitation of LED light sources in waveguide-based spectroscopic sensing applications. This paper reports optical coupling scheme between an LED mid-IR light source and a silicon rich silicon nitride (SiN) waveguide that could enable the use of LED-based light sources. Finally, the detection limit of the investigated device for carbon dioxide gas detection is calculated.

1. Introduction

The potential of silicon photonics was largely based on the use of silicon (Si)-based platforms toward commercialization of photonic devices [1], that are compatible with the existing CMOS fabrication techniques used in most of the well-known electronic devices [2]. For optical interconnect applications, significant progress has been done regarding interconnection between light sources and Si-based waveguides. Optical integration between micro-disk quantum well lasers and external waveguides was reviewed [3].

In spectroscopic sensing applications, the new prospect of using silicon nitride (SiN) strip waveguides was recently discussed [4]. SiN strip waveguides growth on silicon dioxide (SiO_2) exhibit great electromagnetic confinement for a broad range of mid-IR wavelengths. Moreover, wideband gas detection with practical detection limits was also possible based on the absorption of the evanescent field by the targeted gas molecules. The incorporation of a light source was not addressed in [4]. As typical taper structures can be effective only when considering optical coupling between different photonic structures based on the same materials [5], interconnection between LED light sources which will not be Si-based and SiN strip waveguides is worth investigation. Moreover, almost all of the previous works investigate the optical integration based on laser-based light sources, which might prevent the devices from affordable and low power consumption usage [6]. For example, LED mid-IR light sources could have significantly-lower power consumption [7] compared to the laser-based ones.

In this paper, we investigate the optical integration between an LED mid-IR light source and a SiN waveguide on silicon dioxide to identify the optical coupling scheme that could enable the use of LED-based light sources for spectroscopic sensing applications. The efficient optical coupling allows the SiN waveguides to be employed for gas molecule sensing applications with good detection limits. As the refractive indices (n) of SiN can be usefully adjusted over a wide range of values from 2 to 3, it is a very promising platform to be used for on-chip spectroscopic sensing applications considering its flexibility to be specifically optimized for different needs [8-9]. In this proceeding, we focus our report on Si-rich SiN of n ~ 3.

2. Methodology

We employ two well-known techniques of Finite difference time domain (FDTD) and finite difference eigenmode (FDE) to approximate and optimize several parameters of the optical integration scheme between an LED mid-IR light source and a Si-rich SiN waveguide. Figure 1 shows the 3D schematic view and the corresponding side view of the integration scheme under investigation.

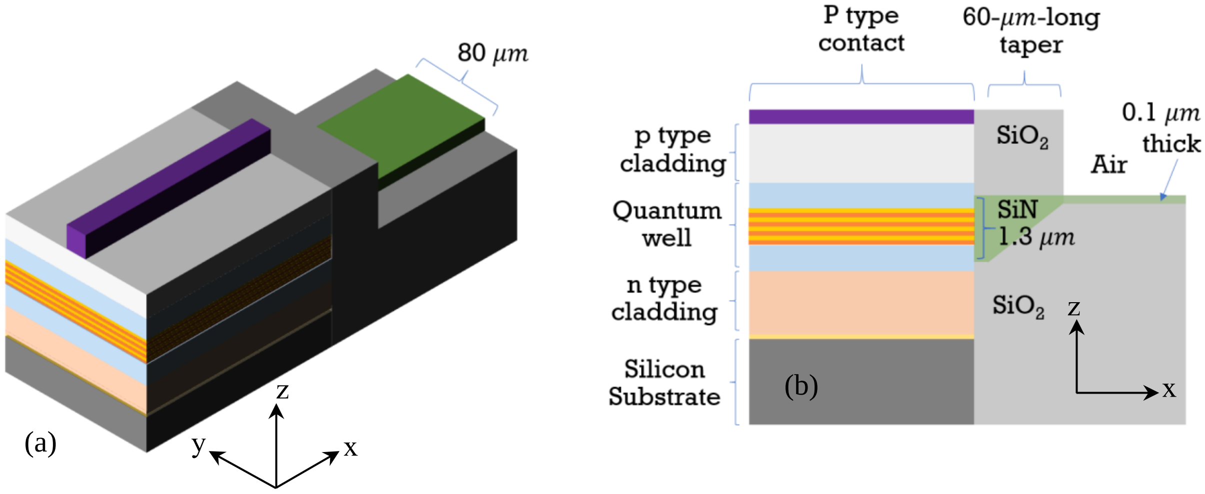

Figure 1. (a) The schematic view and (b) the side view of the structure under investigation.

In this paper, we adopt the LED mid-IR device from [7], in which all of the epitaxial details could be obtained. As in figure 2, from the FDE calculation, we confirm that the LED structure supports single mode propagation of transverse-electric (TE) light at the optical wavelength of ~ 2 µm, which is emitted from the quantum well layers embedded in the structure as indicated in figure 1.

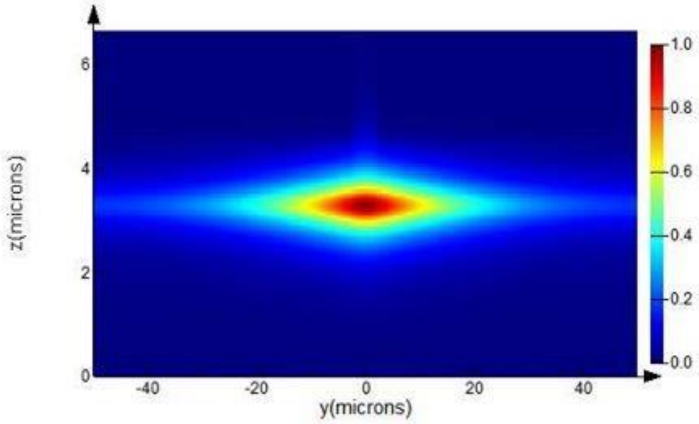

Figure 2. The optical mode profile of the LED mid-IR light source. The structure supports single mode propagation of light at the optical wavelength of ~ 2 µm.

3. Results and discussion

We used the FDTD method to simulate the optical integration between the LED mid-IR light source and the SiN waveguide at the optical wavelength of ~ 2 µm. After optimization, as in figure 1 we arrive at the coupling scheme that consists of a 60-µm-long taper structure which facilitates the optical coupling from LED mid-IR output, connected to the 1.3-µm-high and 80-µm-wide SiN waveguide (to enable an optimized optical mode matching between the LED and the SiN), via the taper to the 0.1-µm-high and 80-µm-wide SiN waveguide to be used for optical sensing based on the absorption of the evanescent field by the target gas molecules. Figure 3(a) shows the optical propagation pattern of the integration scheme from the LED mid-IR light source to the 0.1-µm-high and 80-µm-wide SiN waveguide with air top cladding that could be used for optical sensing. From figure 3(b-d), the coupling scheme can effectively transfer the relatively large optical mode from the LED-based mid-IR light source (as in figure 2) to the compact optical mode of the 0.1-µm-high and 80-µm-wide SiN waveguide. From the 3D FDTD simulation, 68% (as low as 1.7 dB loss, in which ~ 1.1 dB, ~ 0.04 dB, and ~ 0.56 dB are from the LED to figure 3(b), from figure 3(b) to figure 3(c), and from figure 3(c) to figure 3(d), respectively) of the optical power was impressively coupled into the 0.1-µm-high SiN waveguide with air top cladding. Moreover, at the 0.1-µm-high SiN waveguide of figure 3(d), we calculate that the optical mode has as much as 24% of the guided optical power in the air cladding which is comparable to the state-of-the-art report [10] making it promising to be used for spectroscopic sensing based on evanescent field absorption of the sensed molecules. Figure 3(e) reports optical coupling performance over the LED bandwidth of 200 nm from 1.90 µm to 2.10 µm [7]; the coupling performance decreases by less than 3% over the entire wavelength region.

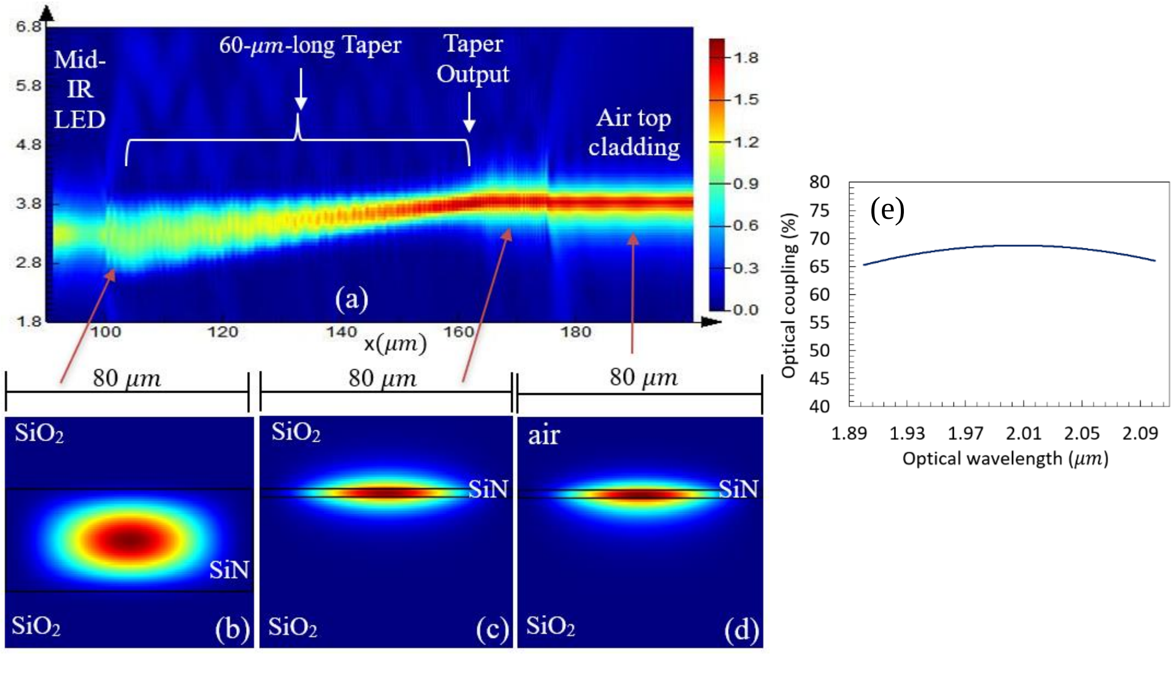

Figure 3. (a) The optical propagation pattern of the integration scheme from the LED mid-IR light source to the 0.1-µm-high and 80-µm-wide SiN waveguide with air top cladding. A 60-µm-long taper structure facilitates the optical coupling from LED mid-IR output, which is connected to (b) the 1.3-µm-high and 80-µm-wide SiN waveguide, to (c) the 0.1-µm-high and 80-µm-wide SiN waveguide and to (d) the 0.1-µm-high and 80-µm-wide SiN waveguide with air top cladding to be used for on-chip spectroscopic sensing based on the absorption of the evanescent field by the targeted gas molecules. (e) Wavelength-dependent optical coupling performance.

The detection resolution could be estimated from [11]

$$C(\text{mol/L}) = -\ln[1-\{(SNR{\bullet}NEP{\bullet}B^{1/2})/P_0\exp(-\alpha L_{opt})\}]/\varepsilon\eta L \quad (1)$$

in which SNR, NEP, and B represent the signal-to-noise ratio, the noise equivalent power, and the bandwidth of the employed detection scheme, respectively. C largely depends on the operating conditions employed in the measurement; hence, we use typical values of SNR = 10, $NEP = 5 \times 10^{-12}$ W/Hz$^{1/2}$, and B = 0.5 Hz (1s averaging time) [4, 11]. P_0(W) is the optical power from the LED which is conservatively assumed to be 1 mW, α(cm^{-1}) is intrinsic optical loss of the SiN waveguide which can be estimated to be 2dB/cm [4], η is the evanescent power factor representing the portion of optical power in the evanescent field as discussed previously ($\eta \approx 24$ %), and L(cm) is the waveguide length which is chosen to be only 2 cm for compactness. Considering the molar absorption of gas molecule ε of ≈ 1.1 Lmol^{-1}cm^{-1} for CO_2 around the optical wavelength of 2 µm [12], it is possible to estimate the detectable CO_2 concentration of around 6 ppm, which is lower than the occupational exposure limit of 5000 ppm for CO_2 recommended by the international environmental standard of the National Institute for Occupational Safety and Health (NIOSH), affirming the potential to employ the proposed integration scheme for gas trace detection in real-time environmental applications thanks to the fact that the coupling scheme can potentially transfer a relatively-large optical mode from the LED-based mid-IR light source to a much more compact optical mode of the SiN waveguide.

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