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Miniaturization of hollow waveguide cell for spectroscopic gas sensing

Jingyi Wei, Yuqing Wei, Xiaosong Zhu, Yiwei Shi*

Key Laboratory for Information Science of Electromagnetic Waves (MoE), Fudan University, 220 Handan Rd., Shanghai 200433, China

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ABSTRACT

Gas sensing system has found applications in industrial process and environmental monitoring. Infrared hollow waveguide is one of the best choices for gas cell in spectroscopic sensing due to the advantages of low loss, flexibility, and fast response. In order to miniaturize the gas sensing system while maintain optical path length, long hollow waveguide can be coiled into a small box to reduce physical dimensions. Bending causes additional loss for hollow waveguide, therefore it is necessary to optimize the parameters for bent hollow waveguide cell. In this paper, a calculation method was established to analyze the performance of a gas sensing system with a bent hollow waveguide as the absorption cell. Simulation results show the relationship between gas absorption intensity and system parameters such as waveguide length, bore diameter, bending radius, system noise, and divergence angle of the light source. Optimized parameters for the waveguide cell were given based on the simulation results. An experimental system was set up by using a Fourier transform infrared (FTIR) spectrometer and flexible hollow waveguides. Preliminary experiments on waveguide length, bending radius, and system signal-to-noise ratio (SNR) were conducted and the measured data agree well with simulation results.

1. Introduction

Gas sensing is in critical demand in a wide range of applications including industrial process, environmental monitoring, and breath diagnosis [1–4]. Among numerous gas detection techniques, gas sensors based on mid-infrared spectroscopic absorption have been extensively studied due to their fast response, high sensing specificity, low drift, and high sensitivity [5].

In recent years, hollow waveguide has been regarded as a potential candidate for gas absorption cell in the spectroscopic gas sensing system. A hollow waveguide [6] is generally defined as a capillary tube with inner coatings of metallic and dielectric films. Laser light propagates with low loss by reflecting at the internal waveguide wall. Low-loss window can be selected by choosing proper film thickness of the dielectric film [7]. AgI coated silver hollow waveguide (AgI/Ag) achieves transmission loss as low as 0.1 dB/m at the wavelength of 10.6 μm for CO_2 laser [8]. Hollow waveguide can simultaneously serve as an efficient transmission medium for infrared radiation and as a miniaturized absorption gas cell owing to its hollow core. The utilization of hollow waveguide as a gas cell provides the advantages of low cost, simple structure and fast response.

Various detection methods in the mid-infrared spectrum based on hollow waveguide have been developed for gas sensing. Kim et al. [9] designed an integrated hollow core optical fiber gas sensor. A 1 m long Ag/AgI hollow waveguide as a gas cell combined with a FTIR enabled continuous detection of small volume gas including CH_4, CO_2, C_2H_5Cl, or their mixtures at trace levels. The limits of detection (LODs) for CH_4, CO_2, and C_2H_5Cl were calculated at 15.8 ppb, 521 ppb, and 1.218 ppm, respectively. Chen et al. [10] demonstrated an ultralow-volume hollow waveguide based carbon monoxide sensor with detection sensitivity of 0.18 ppm. The light source was a vertical-cavity surface-emitting laser radiating at the wavelength of 2.3 μm. The gas cell was a 3 m-long hollow fiber. Absorbance on the order of 10^{-5} was resolvable with the sensor through applying vibration to the fiber with a frequency of 200 Hz. Fetzer et al. demonstrated a gas sensor of CO_2 and NH_3 using a distributed feedback diode laser and hollow waveguide as gas cell. The long hollow waveguide was coiled to reduce the physical dimensions of the system and perforated to reduce the pressure drop caused by long waveguide lengths and high gas flow rates. Order of 10^{-5} has been demonstrated as minimum detectable absorbance [11,12]. Many recent studies have focused on optimization of hollow waveguide. A new generation of hollow

* Corresponding author.
E-mail address: ywshi@fudan.edu.cn (Y. Shi).

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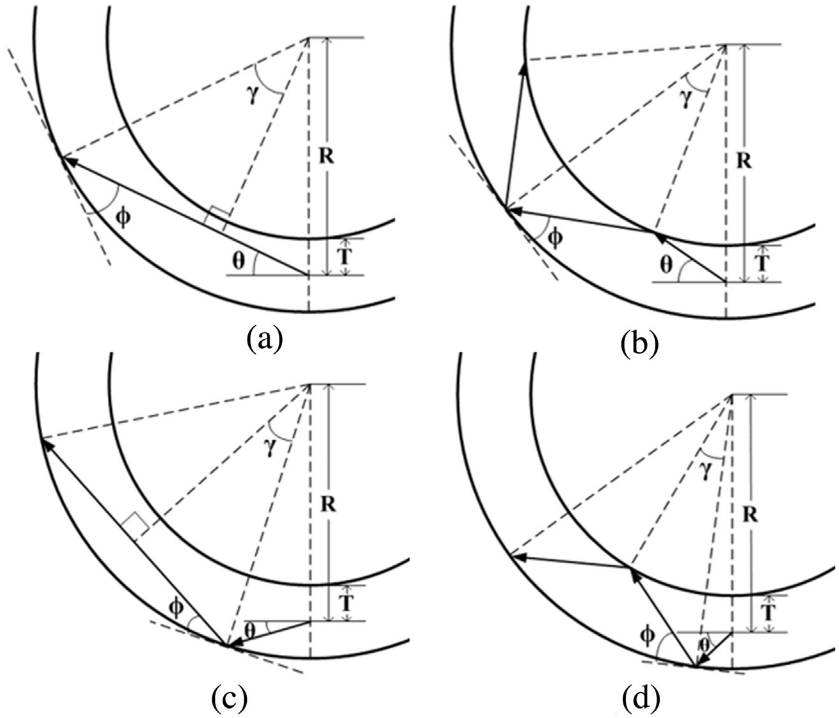

Fig. 1. Light transmission models in a bent hollow waveguide. Incidence towards inside inner-wall with incident angle smaller (a) or larger (b) than critical angle; Incidence towards outside inner-wall with incident angle smaller (c) or larger (d) than critical angle. In Fig. 1, θ is the incident angle, ϕ is the tangential angle with the outside wall and γ is the central angle. R is the bending radius and T is the bore radius of hollow waveguide.

waveguide called substrate-integrated hollow waveguide (iHWG) has been proposed [13] and utilized in gas sensing [14,15]. Design of iHWGs for mid-infrared gas sensors was optimized by Fortes et al. [16]. Three different geometries, i.e. straight, meandering one-turn and two-turn waveguide channels were compared to optimize the achievable LODs.

Although considerable research has been devoted to improving the figures-of-merit of gas sensors based on hollow waveguide, rather less attention has been paid to miniaturization of the absorption cell. Long hollow waveguide can be coiled to decrease physical dimensions while keeping optical length to attain high sensitivity. However, additional loss caused by bending limits the performance of this method [17] since bending attenuation coefficient varies as 1/R with R representing the bending radius [18,19].

With the intention of facilitating compact optical gas sensor based on coiled hollow waveguide while maintaining detection sensitivity, optimized design of bent hollow waveguide was investigated. This paper focuses on quantitative analysis of gas absorbance intensity on the basis of bent hollow waveguide. Through comprehensive consideration of bending loss, gas absorption loss, and system noise, a calculation method was proposed and used to analyze the impact that bent hollow waveguide parameters and system parameters have on optical gas absorption intensity. An experimental gas sensing system based on bent hollow waveguide was also set up to validate the calculation method and to demonstrate the relationship between bent hollow waveguide parameters or system parameters and performance of the gas sensing system.

2. Theoretical calculation

Optical gas sensing using absorption spectroscopy is based on Beer-Lambert Law [20]:

$$I = I_0 \exp(-\varepsilon c l)$$

where I and I_0 are the output and input light intensity of the gas cell, ε is the specific absorptivity of the gas, c is the gas concentration and l is the optical path length of the gas cell. Optical path length l is one of the key parameters in calculating gas absorption in bent hollow waveguide.

To simplify the calculation, only meridional ray is considered in the theory [21]. There are four reflection models when light incidents on the inner-wall of a bent hollow waveguide. As shown in Fig. 1, θ is the incident angle, ϕ is the tangential angle with the outside wall and γ is the central angle. R is the bending radius and T is the bore radius of hollow waveguide.

There exists a critical angle. When light incidents with an angle smaller than the critical angle, reflections happen only on the outside inner-wall of the hollow waveguide. Otherwise, reflections happen on both outside and inside inner-walls. The critical angle is calculated as

$$\theta_c = \arccos\frac{R-T}{R}$$

The relationship between the tangential angle and incident angle can be expressed as

$$\phi = \arccos\frac{R\cos\theta}{R+T}$$

With tangential angle, the central angle can be expressed as

$$\gamma = \begin{cases} \phi, (\theta \le \theta_c) \\ \phi - \arccos\dfrac{(R+T)\cos\phi}{R-T}, (\theta > \theta_c) \end{cases}$$

Optical path length can be computed considering bending radius, bore diameter, tangential angle, and central angle. In order to obtain low-loss property at a target wavelength, a dielectric film with optimum thickness is coated upon the metal layer. It is obvious that optical path in dielectric film has no contribution to gas absorp-