Analytical Study on Slow-Light Orbital Angular Momentum Beams in Vertical Photonic Crystal Waveguides for Gas Detection

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Abstract: We introduce 2D hexagonal air-hole lattice vertical photonic crystal waveguides (VPCWs) to generate orbital angular momentum beams carrying the slow-light effect for on-chip gas sensing through photonic absorption spectroscopy.

1. Introduction:

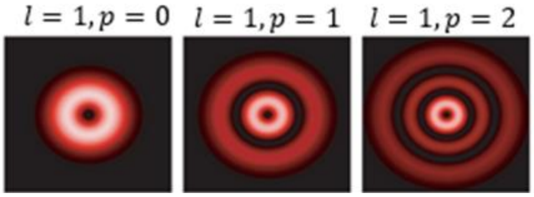

Fig. 1 Laguerre-Gaussian modes: LG01, LG11, and LG21 (left to right) showing the p + 1 concentric rings. [2]

Optical beams, besides energy and linear momentum, can carry orbital angular momentum (OAM), which is dependent on the spatial distribution of the electromagnetic field and is unrelated to the polarization states of the beams [1-2]. A helical wavefront characterizes an OAM beam containing an optical vortex along the axis with a helically rotating phase factor $\mathbf{exp}(\boldsymbol{\theta})$, as shown in Eq. (1), where θ is the azimuthal angle, and l is called an OAM index**.** "$\boldsymbol{l}$" can be any integer number positive or negative. If $l = 0$, the light beam wavefront is not helical but a fundamental Gaussian. If $l = \pm n$, the beam carries left-handed or right-handed orbital momentum, respectively, introducing distinctive spatial structures with the "zero light intensity (a dark vortex core)" at the center, Fig.1(a) [2]. Helically phased OAM light beams are described as the Laguerre-Gaussian modes which have amplitude distributions, LG_{pl}, given by [1-2],

$$LG_{pl} = \sqrt{\frac{2p!}{\pi(p+|l|)!}}\,\frac{1}{w(z)}\left[\frac{r\sqrt{2}}{w(z)}\right]^{|l|} exp\left[\frac{-r^2}{w^2(z)}\right] L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right) \boldsymbol{exp[il\theta]}$$

$$\exp\left[\frac{ik_0 r^2 Z}{2(z^2+z_R^2)}\right] \exp\left[-i(2p+|l|+1)tan^{-1}\left(\frac{z}{z_R}\right)\right] \tag{1}$$

where l is the azimuthal mode and radial mode p is responsible for concentric rings shown in Fig.1, the w(z) is the 1/e radius of the Gaussian term, and $(2p+|l|+1)tan^{-1}\left(\frac{z}{z_R}\right)$is the Gouy phase. $L_p^{|l|}$ is an associated Laguerre Gaussian polynomial. The start-of-the-art applications in OAM optical beams include optical communications, quantum information systems, optical sensing, imaging, and manipulation of microparticles. OAM light beams are currently generated by manipulating spatial phases with many devices, including a Spatial Light Modulator, spiral phase plates, computer-generated holograms, and so on [3]. Many more applications based on OAM light will likely require miniaturized photonic integrated devices and circuits to enhance performance and functionality.

This work presents our analytical studies in which optical beams carrying OAM modes are generated when introducing a central defect hollow core in a two-dimensional (2D) hexagonal air hole lattice vertical photonic crystal waveguide (VPCW). The VPCW gas sensor fabricated on a silicon slab has perfect periodic air holes as cladding in a 2D hexagonal photonic crystal arrangement, giving rise to photonic bandgaps (PBGs) at a specific range of frequencies. The VPCW sensor with a hollow core defect and hexagonal lattice consisting of air holes in the silicon slab is shown in Fig.2(a). By introducing the defect, the optical OAM modes with a slow group velocity can be confined and guided through the defect core due to the complete bandgap of hexagonal lattice photonic crystal. The hollow core defect acts as a waveguide where ambient gas species can interact with slow light-assisted light beams with the group velocity, $v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$, enhancing the effective interaction pathlength, L given by Beer-Lambert's law, $I = I_0 \exp\left(-\gamma \alpha_{abs} L\right)$, where c is the speed of light, n_g is the group

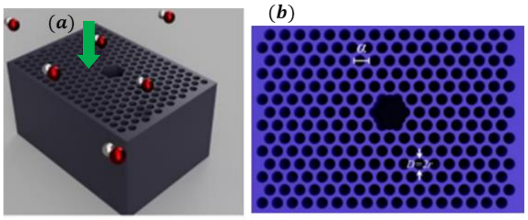

Fig.2 (a) Schematic illustration of the hexagonal photonic crystal with the hollow core defect. (b) Top-View of the device.

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refractive index, $\frac{\omega}{k}$ is the dispersion relation, I and I_0 are transmitted and incident intensity, α_{abs} is the absorption coefficient, and γ is the medium-specific absorption factor. Generally, 2D structure PCW fabricated on silicon or silicon on insulator (SOI) has been considered for applications that use slow-light effects, such as optical buffers, optical delay lines, optical switches, and optical sensing [4-6]. Our miniaturized and photonic integrated VPCW-based device that can generate slow light OAM beams will pave the way for many more promising applications such as quantum computing and sensing, biomedical applications where deep penetration of light requires complex encryptions, advanced multiplex optical communications, and environmental gas sensing.

2. Design, Simulations, and Results

Fig. 2(a) presents a schematic depiction of the VPCW sensor structure and its operational principle. The air holes with a radius denoted by r = 0.22α. A top-view schematic representation is illustrated in Fig. 2(b), where D = 2r = 2.362 μm represents the diameter of the holes, and α = 1.4991 μm is the PC lattice constant. In Fig. 3 (a-c), the electric field profile of the Orbital Angular Momentum (OAM) modes is displayed through Finite-Difference Eigenmode (FDE) analysis. Recognized higher-order Hermite-Gaussian modes HG01 (Fig. 3a) and HG10 (Fig. 3b) superimpose to generate a helical OAM beam, LG01, as depicted in Fig. 3c.

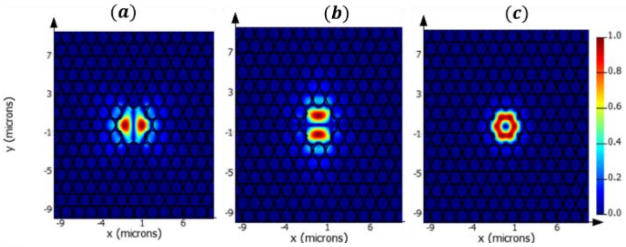

Fig.3 (a-c) Intensity pot of OAM mode generated in the hexagonal PC with the hollow core defect. Superposition of Hermite Gaussian mode HG_{01} and HG_{10} to produce Laguerre-Gaussian mode LG_{01}.

The OAM beam, carrying a group index (n_g) of ~215 in the designed VPCW, represents a bound and slow mode within the photonic bandgap, showing minimal leakage from the core. *This characteristic enhances absorbance by extending the effective path length in a compact physical device*. Our additional simulations show complex patterns in higher LG modes, such as LG31 and LG0-3+LG03, illustrated in Figs. 4(a) and 4(b).

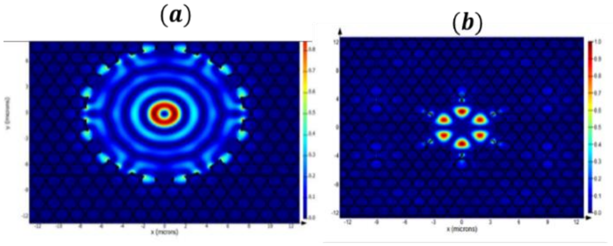

*Fig.4 Laguerre-Gaussian modes (a) LG_{31} **(b)** LG_{0-}*

Utilizing Orbital Angular Momentum (OAM) Laguerre-Gaussian modes with slow-light characteristics [7] in photonic crystals with defects holds tremendous promise for gas sensing applications. Specifically, we focus on employing these optical beams in a miniaturized on-chip gas sensor optimized for greenhouse gas (methane) detection at its mid-IR absorption wavelength of 3.31 μm.

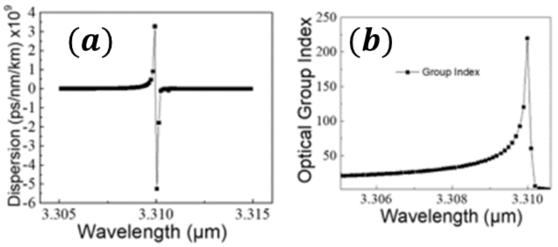

Fig. 5 (a-b) Optical mode characteristics of bounded defect mode as a function of wavelength.

In Fig. 5(a-b), the calculated dispersion and group index characteristics indicate that, at the ratio of $a/\lambda = 0.45$, the slow light effect yields an exceptionally high group index. The optimized defect radius is positioned at approximately 118% of the crystal period (a) to achieve this, effectively confining the slow-light mode within the defect region. In simulations, the calculated group index and dispersion at 3.31 μm are determined to be 215 and 3.27*109 ps/nm/km, respectively. This unique combination of OAM beams and slow-light features offers significant potential to improve the sensor's sensitivity and specificity, enabling efficient gas sensing across various wavelengths. We are actively engaged in ongoing efforts to refine the design and conduct experimental measurements, aiming to enhance the performance of the on-chip absorption sensor for robust gas sensing applications.

In conclusion, our analytical study demonstrates the photonic integrated VPCW capability to produce helically phased OAM Laguerre-Gaussian modes with slow-light characteristics, featuring a considerably large group index value of ~215. We present the design application, specifically highlighting absorption spectroscopy within a miniaturized on-chip gas sensor optimized for slow light mode at 3.31 μm for methane detection. Ongoing design modifications and experimental measurements are underway to enhance sensing sensitivity. This research received support from the NASA STTR Phase I program under Contract # NASA-80NSSC22PB125.

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